SPECIAL REPORT 97-15

CRREL

Ground Freezing Effects on Soil Erosion of Army Training Lands

Part 1: Initial Test Results

Lawrence W. Gatto

August 1997

Abstract: Military maneuvers damage vegetation and compact and rut soils on training lands, thereby increasing the likelihood of hillslope runoff and soil erosion. Soil Freeze–Thaw (FT) processes can change the hydraulic geometry and roughness of vehicular ruts and reduce soil compaction, which often partially restores the water infiltration rate that existed before compaction. The efficiency of these FT-induced "repairs" depends on soil water content and FT intensity. Initial tests showed that 1) an experimental soil bin designed and constructed for rut experiments allows acceptable simulation of field soil FT, and 2) the hydraulic geometry of a rectangular rill in a fine silt soil with an initial volumetric water content of 36% changes dramatically due to rill sideslope slumping during thaw. Future experiments will compare differences in the response of natural rills and vehicular ruts to FT-induced soil failure, and investigate the effects of FT on soil erodibility and the influences of snow cover on soil erosion processes in the spring.

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US Army Corps of Engineers®
Cold Regions Research & Engineering Laboratory

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Part 1: Initial Test Results

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August 1997

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Lawrence W. Gatto, Geologist, Geological Sciences Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

The author thanks Dr. Gurdarshan Brar, Antonio Palazzo, and Sally Shoop for technically reviewing the manuscript; Edwin Chamberlain, Robert Eaton, Kurt Knuth, Carl Martinson, James Morse, Antonio Palazzo, Sally Shoop, and Jeffrey Stark for numerous discussions and advice during the planning of the initial tests; Carl Martinson, Richard Roberts, Stephen Pugh, Lewis Nichols, Robert Eaton, and James Morse for assisting with the experimental setup; Paul Schwarz for cycling the refrigeration system; and Robert Demars and Carl Martinson for taking photographs during the setup and tests. Funding is from the Office of the Chief of Engineers, CERD-M, through the 6.1 Environmental Quality Technology Program, Conservation Pillar, Geomorphological Process Modeling Thrust, under project *Soil Erodibility and Runoff Erosivity Due to Soil Freezing and Thawing* (BT25-EC-B10).

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NOMENCLATURE

A = cross-sectional flow area

C, n = roughness coefficients

d = rill cross-sectional depth

F = freeze

F1 = first freeze

F2 = second freeze

FERF = Frost Effects Research Facility

FT = freeze–thaw

FTC = freeze–thaw cycle

Q = runoff volume

R = hydraulic radius

RG = resistivity gage

S = channel bottom slope

T = thaw

T1 = first thaw

T2 = second thaw

T_a = air temperature between freezing panels and soil surface in bin

T_p = panel temperature

T_{ssc} = temperature of the soil next to RG C

T_{ssr} = temperature of the soil in mid-rill

V = flow velocity

w = rill width

Ground Freezing Effects on Soil Erosion of Army Training Lands
Part 1: Initial Test Results

LAWRENCE W. GATTO

INTRODUCTION

Soil erosion

Soil is naturally eroded by water flowing down bare or partially vegetated hillslopes; this erosion is a function of the erodibility (detachability) of soil particles and the transport power of flowing water (Table 1). Soil erodibility is a function of interparticle friction, bonding, and interlocking. The strength of these particle interactions depends on soil particle size and distribution, soil structure and structural stability, soil permeability, water content, organic matter content, and clay, mineral, and chemical constituents (Lal and Elliot 1994). Crusts that often form on soil surfaces also increase the resistance of soil particles and aggregates to erosion.

In addition, vegetation cover significantly influences the amount of soil erosion at a location by 1) binding surface and near-surface soil particles through root–soil bonds, 2) reducing rainfall erosivity by intercepting free-falling raindrops and reducing the number and kinetic energy of raindrop impacts onto the soil surface (Evans 1980), and 3) reducing overland flow velocities by increasing friction where plant stems protrude into the flow (Prosser et al. 1995). Thus, any process that alters either the physical strength of a soil or reduces its vegetative cover increases the likelihood of water erosion of that soil.

Effects of Army maneuvers on training land erosion

The Army is responsible for over 18,500 square miles (4.8×10^4 km^2) of training lands that are principally used to ensure the military readiness of its units (Doe 1992). Trainers must maintain realism during maneuvers, but the goals of readiness and realism often conflict with environmen-

Table 1. Factors that determine the severity of water erosion. (After Lal 1994.)

I. Climatic erosivity

1. *Rainfall erosivity*
   - A measure of the ability of rain to detach sediment particles and surpass the infiltration capacity of soil so that overland flow begins.
   - Also called the Energy-Intensity (EI) parameter, a function of rainfall volume, raindrop impact, and peak intensity.
2. *Runoff erosivity*
   - A measure of the ability of flowing water to detach and transport sediment particles.
   - A function of runoff volume and peak flow.

II. Soil erodibility

- A measure of the susceptibility of sediment particles to being detached and transported by rain and flowing water.
- A function of soil texture, structure, permeability, organic matter content, chemical constituents, and clay mineralogy.

III. Topography

- Hillslope length, steepness, and shape influence overland flow velocities and turbulence, which partially determines the likelihood of rill formation.

IV. Land use

- Disturbance to a soil surface influences the effectiveness of raindrop impacts in moving soil particles, soil infiltration rates, and overland flow velocities and turbulence.

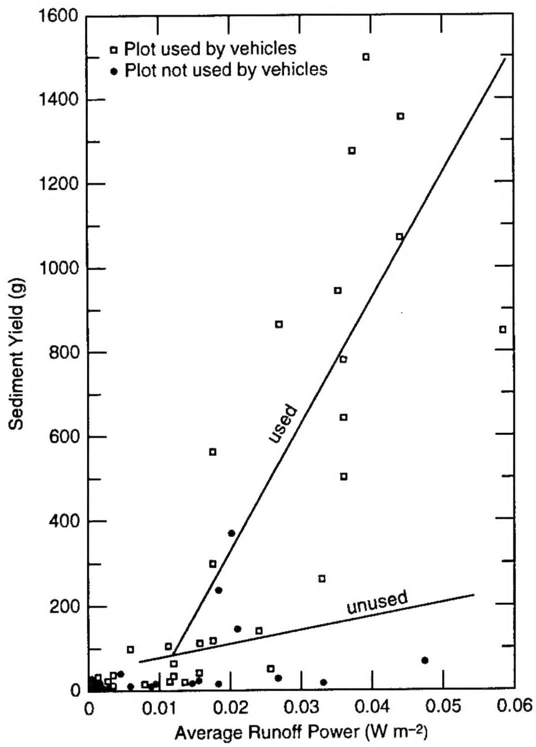


Figure 1. Runoff power vs. sediment yield from 1-m² erosion plots used and not used by off-road vehicles. (After Iverson 1980.)

tal requirements. Army land managers, who need to preserve natural resources on training lands, are required to minimize vegetation damage and soil disruption, which inevitably occur during training. Vegetation and soils are important resources in themselves, but damage to them often leads to accelerated soil erosion (Dregne 1983).

An armored unit on the move or an infantry march damages vegetation, breaks up soil crusts, loosens surface soil, alters soil structure, weakens soil aggregates, changes soil surface roughness, changes the shape and number of surface depressions, and often compacts soils. Compaction increases soil bulk density, reduces infiltration and hydraulic conductivity (Voorhees et al. 1979; Webb 1983; Thornes 1980; Braunack 1986a,b; Ayers 1994; Campbell 1994; Horton et al. 1994), and restricts soil aeration, which impairs root growth, plant nutrient uptake, and seedling emergence (Chancellor 1977, van Ouwerkerk 1991, Stepniewski et al. 1994). Thurow et al. (1993) report that recovery of damaged plants and new growth is often limited on compacted soils. This results in a vegetative cover that is too sparse or composed of species less effective in protecting and binding soil particles sufficiently to contribute to their stability and flow resistance.

The impact of soil compaction on hillslope hydrology and erosion processes is substantial. Rainfall of a given intensity, which usually infiltrates into undisturbed soils, often does not infiltrate into the same soils if compacted. Vehicular ruts formed during maneuvers often have compacted soils beneath and adjacent to them. This additional surface water adds to runoff volumes (Eckert et al. 1979, Mathier and Roy 1993) and makes runoff periods longer (Hinckley et al. 1983). I believe that the ruts tend to channel the additional runoff into rill-type flows, with velocities that may be measurably higher than velocities in natural rills on the same hillslope. Natural rills don't carry any additional runoff coming from compacted soils. I suggest that such higher runoff erosivity in ruts may explain why gullies on training lands can form and enlarge faster than they do on adjacent undisturbed soils.

Iverson (1980) showed that, for a given runoff power, more sediment was eroded from hillslope plots that were used by off-road vehicles than from those that were not used (Fig. 1). He reported that the flow capacity on used plots increased more than linearly with runoff power because of increased runoff volume and flow channelization. Reduced infiltration and frictional resistance to flow on used plots cause overland runoff to happen more rapidly and attain an eroding discharge over a larger portion of a used hillslope than on an unused slope.

EFFECTS OF GROUND FREEZING ON MANEUVER IMPACTS

Soil compaction

Soil compaction is the compression of unsaturated soil because of reduction of its air-filled pore space without a change in mass wetness. Compaction results from simultaneous application of vertical pressures and shearing stresses from trafficking on soils (Hillel 1980). The amount of vehicular soil compaction is determined by vehicle type, pattern of loading (static, dynamic, stable, vibratory), vehicle-traffic motion (straight or turning), number of vehicle passes, vehicle pressures applied, soil texture, density and moisture, and state and stability of soil structure (Voorhees et al. 1978, 1986; Akram and Kemper 1979; Hillel 1980; Webb 1983; Gupta et al. 1989; Braunack 1986a,b; Foltz 1992; Thurow et al. 1993).

Depending on the interplay of these factors, a compacting vehicular force (applied load)

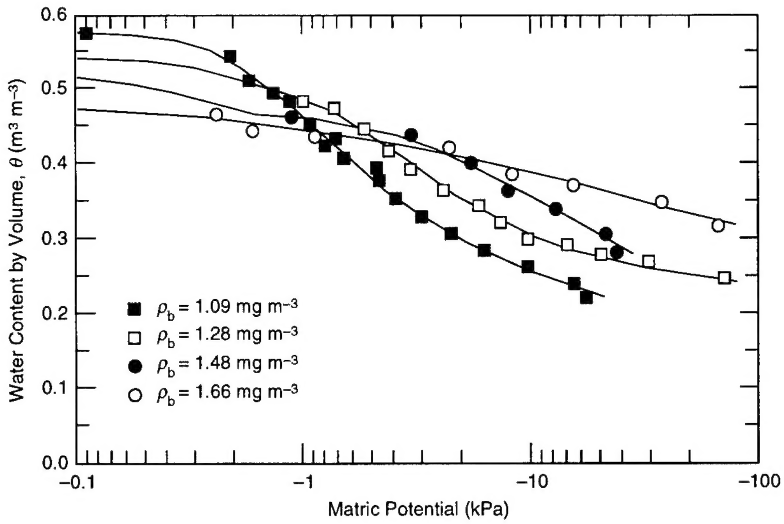


Figure 2. Water retention characteristics of Nicollet clay loam at various bulk densities; dense soils hold less water at high matric potential and more water at low potential. (After Gupta et al. 1989.)

- Establishes or breaks bonds in aggregates and among particles (Koolen and Kuipers 1983).
- Crushes soil aggregates, thus making the soil particle distribution more uniform, which tends to reduce soil pore size distribution, which changes the soil water suction and water retention characteristics (Taylor and Box 1961, Koolen and Kuipers 1983, Gupta et al. 1989, Cruse and Gupta 1991) (Fig. 2).
- Increases the volumetric water content because the applied stresses act for a very short time during compaction, which strongly restricts the amount of water that moves out of the soil, i.e., traps the water (Hillel 1980, Koolen and Kuipers 1983).
- Reduces the volume of soil voids, which reduces total porosity and increases dry bulk density (Hillel 1980, Kooistra and Tovey 1994).
- Changes soil pore geometry (Gupta et al. 1989) and reduces the interconnectedness of larger pores (Hillel 1980, Iverson 1980).
- Increases soil penetration resistance (Voorhees et al. 1986), especially with rubber tires, not tracks (Braunack 1986b).
- Decreases soil infiltration (Akram and Kemper 1979) (Fig. 3) and permeability (Braunack 1986a,b); and if, during trafficking, the vehicles' wheels slip, realigns soil particles parallel to the direction of the shear forces, which causes additional compaction and further reduces infiltration (Gupta et al. 1989).
- Increases surface runoff and accelerates soil erosion (Foltz 1992, van Ouwerkerk and Soane 1994).

Compacted soil particles can be loosened by the shrinking and swelling associated with wetting and drying of clays (Larson and Allmaras 1971), by root growth and by soil freeze–thaw (FT), so that the infiltration rate of a previously compacted soil often returns to or near to its previous values (Canarache 1991, Thurow et al. 1993). The ice that forms in soil pores during freezing can reduce the density of compacted soil by pushing soil grains apart and reducing their degree of interlocking. This is most effective when volumetric soil water content approaches soil porosity. The amount of soil ice formed in pores or as lenses is related to the volume of soil water present when freezing starts and the volume drawn to the freezing zone from the subsoil (Miller 1980).

Upon thawing, a soil is usually less dense, although the degree of FT-induced soil expansion depends on soil water content, soil texture and depth, the rate of frost penetration, the number of FT cycles, and the depth of compaction (Webb et al. 1983). This soil loosening can be sufficient to increase infiltration and reduce runoff, especially in arid and semi-arid environments (Schumm and Lusby 1963). However, research results to date conflict regarding the degree of FT-induced loosening, as discussed below.

Chamberlain and Gow (1979) found that FT reduced void ratio and increased vertical permeability, while Blake et al. (1976) found that FT did

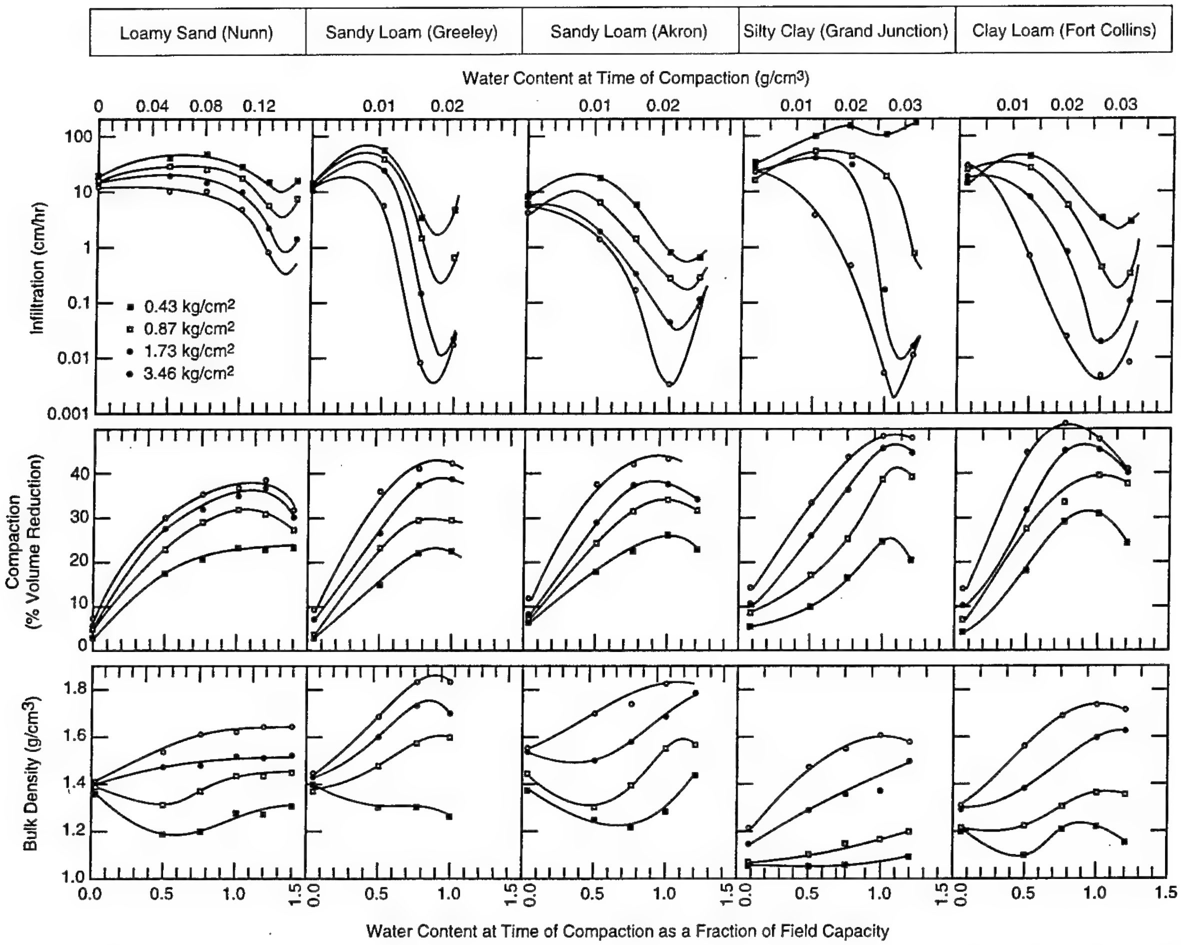


Figure 3. Effects of compacting loads and water content on infiltration rate, compaction, and bulk density. (After Akram and Kemper 1979.)

not reduce bulk density of compacted Nicollet clay loam in Minnesota at 20–30 cm depth, even after 9 years. Akram and Kemper (1979) reported that FT reduced soil compaction in different soils and, as a result, infiltration rates increased after FT. Infiltration increased most after one FT cycle in a loamy sand, after two cycles in one sandy loam and three cycles in another sandy loam, and infiltration was still increasing in a clay loam after four cycles (Fig. 4).

Voorhees et al. (1978, 1986) suggested that the persistence of soil compaction in agricultural fields, despite FT cycling, may be partly attributable to increasing tractor weight. FT loosened the soil to about 20 cm but compaction persisted below 20 to 90 cm depth where it was unaffected by FT (Fig. 5); however, this persistence was in part soil-dependent. Voorhees (1983) reported that soil FT and wetting and drying reduced soil penetration resistance by 20–50% and that the FT was more effective in reducing resistance when the soil was wetter at freezeup.

The above results may differ because of the real variability in nature and the absence of standardized methods for characterizing soil compactness (Soane and van Ouwerkerk 1994), although soil bulk density, total porosity, void ratio, specific volume, and unit weight are generally considered to be fundamental criteria that define the degree of compaction.

Vehicular ruts

Vehicles can rut a soil surface, depending on vehicle load in relation to soil conditions at the time of trafficking (Richmond et al. 1995). Ruts are potential sites of high soil erosion when aligned directly up and down slope and are hydraulically similar to natural rills in the erosivity of the flows in them. Water flow is faster and more turbulent in natural rills than it is in overland sheet wash (Evans 1980) and it has more energy to detach and transport sediment.

Voorhees et al. (1979) reported that the ruts left by wheeled vehicles can act as channels to concen-

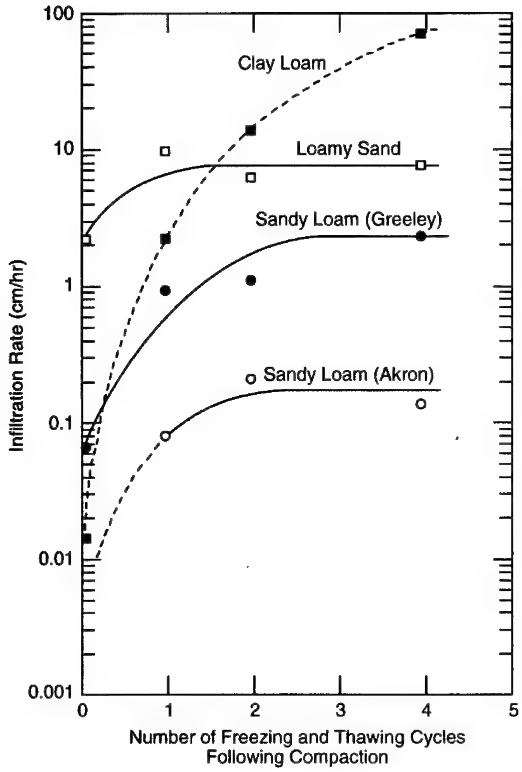


Figure 4. Effect of FT cycles on infiltration rate of compacted soils. (After Akram and Kemper 1979.)

trate surface runoff, which increases its sediment transport capacity and subsequent soil erosion. Foltz (1993) determined that there is 200–400% more erosion on rutted roads than on unrutted roads. Morgan (1977) determined that rill sediment transport exceeded that on inter-rill surfaces by a factor of 40 on an 11° slope. Mutchler and Young (1975) determined that more than 80% of eroded hillslope sediment is transported in rills, and Meyer et al. (1975) reported a threefold increase in soil loss following rill development on a hillslope. Thus, rill (and rut) erosion is a geomorphically significant process (Slattery and Bryan 1992).

The intermittent flows in rills and ruts are usually appreciably deeper than the height of the coarsest roughness elements within them and, in this regard, are hydraulically similar to conventional open-channel flows in rivers (Thornes 1980, Hairsine and Rose 1992). The erosivity of such flows is directly related to runoff volume and velocity

$$Q = AV$$

where Q = runoff volume
A = cross-sectional flow area
V = flow velocity.

The velocity is determined by channel roughness, cross-sectional shape, and slope and can be estimated by the Chezy (eq 1) or Manning's (eq 2) equations

$$V = C\sqrt{RS} \tag{1}$$

$$V = 1.49/n\ R^{2/3}\ S^{1/2} \tag{2}$$

where V = flow velocity
C, n = roughness coefficients
R = hydraulic radius, A/P (P, wetted perimeter)
S = channel bottom slope (approximately).

It is apparent that processes that change rill or rut cross-sectional shape can have a major influence on flow erosivity and thus on sediment

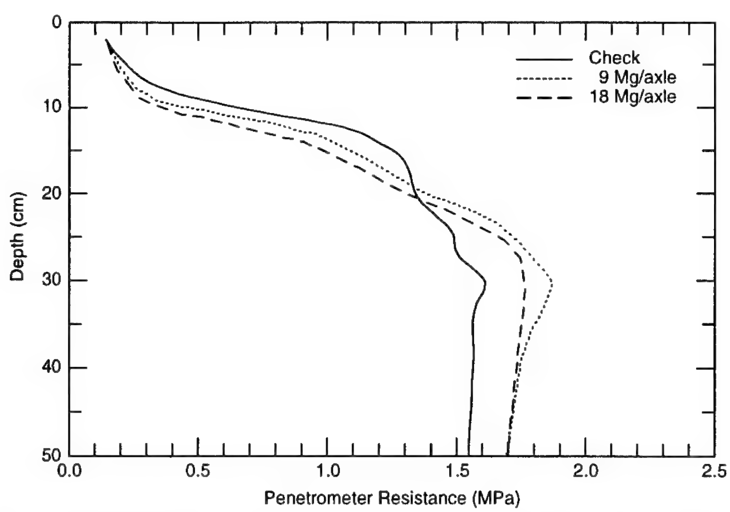


Figure 5. Penetrometer resistance 4 years after initial loading of Webster clay loam in Waseca, Minnesota, with a wheeled vehicle. (After Voorhees et al. 1986.)

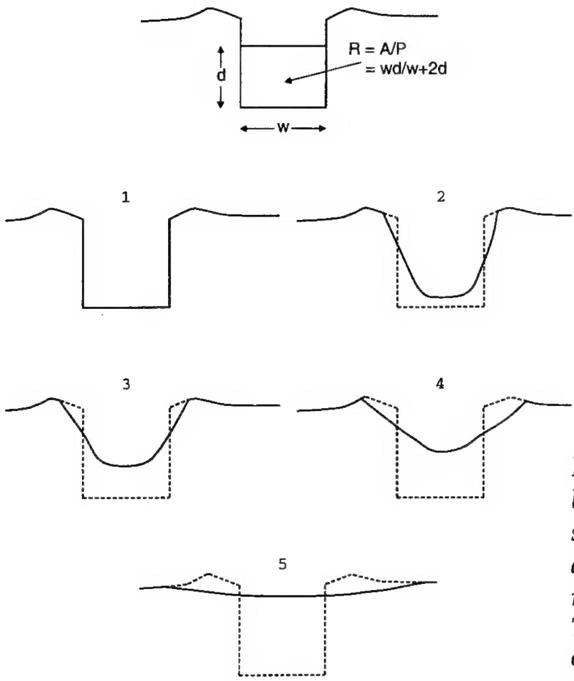


Figure 6. Hypothetical changes in rill hydraulic geometry because of FT-induced soil failures; as thawed soil along rill side slopes collapses, the rill cross-sectional depth (d) *decreases and width* (w) *increases, and the character of the rill flow becomes more like that of less-erosive overland flow. This evolution assumes no intermittent flow to clean out the rill channel.*

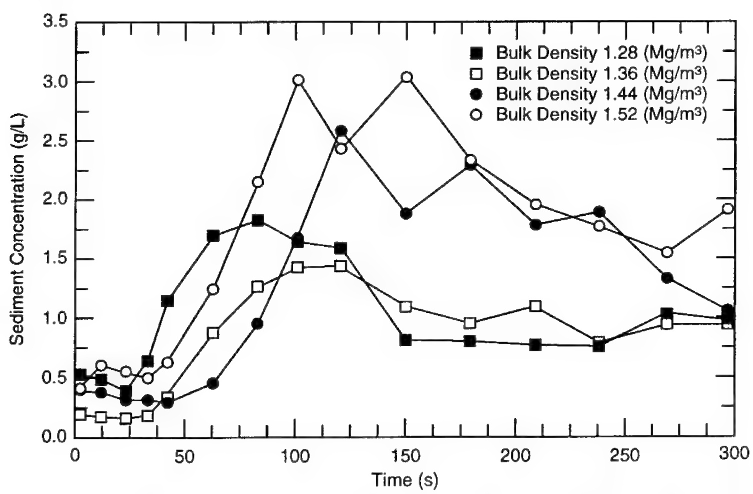


Figure 7. Sediment concentrations in runoff over variably compacted soil was higher in denser soil because the surface roughness of and the infiltration into the more compacted soil was less, resulting in high, near-bed water velocities and more bed soil-particle detachment and transport. (After Parker et al. 1995.)

transport and hillslope erosion. In some locations, frost-induced soil creep is more effective at moving surface soils downslope than is summer creep and can obliterate natural rills over one winter (Schumm and Lusby 1963; Schumm 1956, 1964, 1967; Carson and Kirkby 1972). Such rills become clogged with sediment and the initial runoff in the spring often becomes sediment laden as it clears out infilled rills (Schumm and Lusby 1963). Thus, rill enlargement often results from sediment infilling processes and sediment clearing and channel cutting by rill flows (Kirkby 1980, Piest et al. 1975). Owoputi and Stolte (1995) state that further study of the characteristics of rills is necessary for an improved prediction of the soil erosion process.

I hypothesize that the cross-sectional shape of a rill would become broader and shallower after FT-induced failures along the rill side slopes and no intermittent flows (Fig. 6). As a rill's depth

decreases, bankfull flow within it tends toward sheet flow, where width is much greater than depth. Thus, the amount of hillslope erosion taking place in such a rill could be less than that in a rill unaltered by FT. In nature, sediment infilling and channel alterations by FT-induced soil creep occur in conjunction with sediment transport by intermittent flows, and rill cross-sectional shape is determined by hydraulic and soil processes in northern climes.

I am unaware of studies that have compared erosion on a compacted and rutted hill to that on an undisturbed, rilled slope, but I hypothesize that the transport capacity of vehicular ruts may be changed by FT processes as are rills. However, the ruts may not infill as rapidly as natural rills because the compacted soil along a rut may have higher shear strength, which may temporarily retard FT-induced creep down the rut side slope. Thus, I also hypothesize that erosion on a rutted hill could be more severe. First, flows in ruts may have higher velocity and, thus, higher stream power than rill flows. Parker et al. (1995) found that flow velocity near the soil bed increased with bulk density (compaction), because surface roughness was less in the more compacted soil, and that sediment concentration in runoff was higher on more highly compacted soil (Fig. 7). They found that the increased velocity from compaction had more effect on erosion than the increased soil shear strength. Second, the volume of surface water would be greater on a compacted slope than on the undisturbed slope, owing to reduced infiltration. Third, the compacted soil around a rut would allow less infiltration along its length than may occur along a rill on the same slope; thus, the erosivity of rut flow could be maintained for greater distances downslope. Research comparing rill and rut processes is planned as part of this project.

Seasonal soil erodibility

While FT can loosen compacted soil and smooth rills, and possibly ruts, over time, it can also make undisturbed soils more erodible in the spring than they are at other times of the year (Gatto 1995). When soil water freezes in the winter, the ice crystals can disrupt soil grain interlocking, which results in a less dense, weak soil upon thaw. In addition, the soil water content in a freezing soil usually increases as moisture is drawn from the unfrozen soil below to the freezing front. Thus, newly thawed soil usually has more water than before it froze (it may be temporarily saturated), which contributes to its low strength and makes it highly susceptible to downslope movement by gravity, detachment by raindrops, and detachment and transport by overland flow.

The magnitude of these FT-induced effects is variable, however; Benoit and Voorhees (1990), and Kok and McCool (1990) report that FT effects are some of the least understood aspects of the soil erosion process, even though soil FT processes have been investigated for years. In addition, current erosion models still cannot predict infiltrability or erodibility in frozen and partially frozen soils at their surface (Seyfried and Flerchinger 1994), even though Young et al. (1993) have developed a method to predict soil frost depth as part of the Water Erosion Prediction Project (WEPP) soil erosion model.

Knowledge of the role of snow cover on soil erosion mechanics remains rudimentary as well. Haupt's (1967) research showed that a snow cover tends to insulate and thus preserve soil frost, even during spring rains, by preventing raindrops from contacting the frozen soil. His study shows that because the soil remains frozen under snow-covered plots and is very resistant to flow, virtually no soil is eroded, even though the vegetation below the snow is sparse.

A significant portion of previous soil erosion research has been directed at changes in soil bulk properties, not changes in surface soil structure and strength, which are most important to erodibility. Shainberg et al. (1994) point out that soil detachment by rill or overland flows depends on soil-particle-binding forces at the soil/water interface, not bulk-tensile-strength properties of the soil at depth. Yet, bulk soil strength properties are often measured and used to predict soil erodibility.

Misra and Rose (1995) summarized research on the relationships between soil strength, as measured in the field, and soil erodibility, as defined by the amount of soil particles moved by rain splash and runoff. However, that relationship remains unclear, and the need for a method to predict seasonal soil erodibility over time persists, which impedes improvements in our ability to predict soil erosion (Nearing et al. 1994).

RESEARCH NEEDED AND PROJECT GOALS

Clearly, soil freeze–thaw cycling is a dynamic process, substantially affecting runoff and soil erodibility during the year. And the most important experimental topics in the soil erosion arena are the dynamic processes that determine soil

resistance to hydraulic forces and determine runoff formation rates and volumes (Kirkby 1980, Gerits et al. 1990). Papendick and Saxton (1990) reported that research on frozen soil effects remains a high priority. Cooley (1990) described the importance of incorporating the effects of FT on soil compaction and strength, runoff, and erosion into soil erosion models. In spite of the accelerated erosion that often results from Army maneuvers, past research has not determined the significance of FT in alleviating vehicular compaction, in reestablishing soil infiltration, in changing rut geometry, and in determining sediment-transport capacity on training lands.

Available research results conflict regarding the efficacy of FT in reducing vehicular compaction, do not define the basic soil–FT processes involved, and are absent regarding FT effects on vehicular ruts. The effects of FT on natural rills has been investigated at a preliminary level. And we know that snow cover can retard soil thaw and absorb raindrop impact energy, but we lack details on how snow affects soil particle detachment on the soil surface and affects soil creep along rills and ruts.

Laboratory and field experiments will be conducted to

- Measure FT-induced changes in shear strength, penetration resistance, infiltration rates, and surface geometry and roughness of compacted and rutted soils for different FT regimes, compaction loads, and soil type and water content.
- Determine if compaction and ruts from tracked and wheeled vehicles are affected differently by soil FT.
- Determine differences in the cross-sectional shapes of rills and ruts caused by FT-induced soil creep.
- Evaluate how and to what degree soil FT rates and soil water contents affect soil shear strength and penetration resistance (soil erodibility) of different soil types.
- Use rainfall simulators to determine soil erodibility with various antecedent soil water conditions and soil types, and rainfall erosivity before frost and after thaw on different slopes.
- Determine if snow cover alters the temperature gradient in the soil sufficiently to reduce the amount of water drawn to a soil freezing zone.
- Evaluate the effects of snow cover on the amount of thaw creep along rills and ruts.
- Investigate soil particle detachment under snow.

Laboratory studies will include large- and small-scale experiments carried out in the Frost Effects Research Facility (FERF) at CRREL and small-scale experiments in coldrooms. Field research will be done in three hydro-climatic regions: the cool, semi-arid zone of south-central Washington at the Army's Yakima Training Center (YTC), the cold, humid area of upper New England at CRREL or Ethan Allen Firing Range (EAFR), Vermont, and the cold, dry climate of the upper midwest, possibly at Camp Ripley, Minnesota, or Fort McCoy, Wisconsin. The studies at YTC and EAFR are currently underway.

This research will extend existing knowledge of soil erosion mechanics, developed for the traditionally agricultural and rangeland settings, to military training lands where soil frost forms. It will provide information to terrain modelers to help improve their simulations of seasonally dynamic soil processes that significantly influence terrain evolution and hillslope soil processes. The research results may eventually be used to modify the Revised Universal Soil Loss Equation (RUSLE) and WEPP soil erosion models to better simulate the effects of winter processes and conditions on runoff erosivity and soil erodibility, information that is now unavailable to Army land managers.

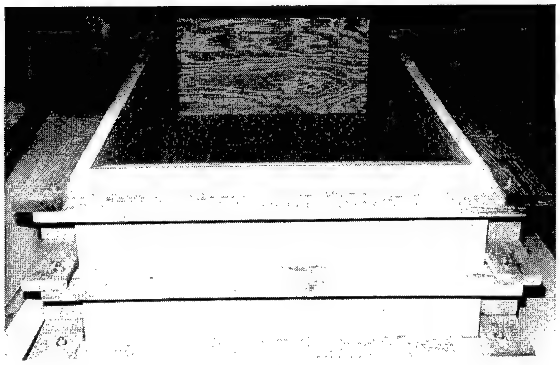
OBJECTIVES OF THE INITIAL TESTS

The objectives in these tests were 1) to see if I could achieve the freeze rates in the soil bin located in the FERF that would allow me to do my planned experiments, 2) to determine if the soil in the bin would freeze and thaw in a natural fashion and, thus, reasonably simulate field conditions, 3) to evaluate the operation and adequacy of the instruments to be used in future experiments with multiple bins, and 4) to measure cross-sectional changes in a simulated, rectangular rill.

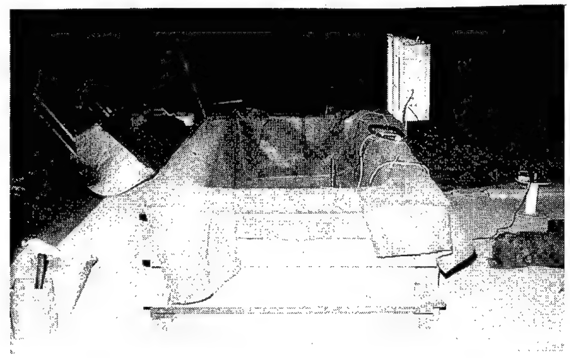
APPROACH

Bin construction

The first bin was constructed with two layers of pressure-treated, $^{3}/_{4}$-in. (1.9-cm) plywood, reinforced with pressure-treated, 2- × 6-in. (5- × 15-cm) boards and insulated with one layer of 2-in. (5-cm) polystyrene foam board on the sides and bottom (Fig. 8a). The inside of the bin was lined with an impermeable membrane (Fig. 8b) that was trimmed and tacked to the interior walls. The bin in final position for these first tests was horizontal along its long axis but sloped from its east side to its west approximately 0.5 in. in 4 ft (1.3 cm in 1.2 m). The bin is a



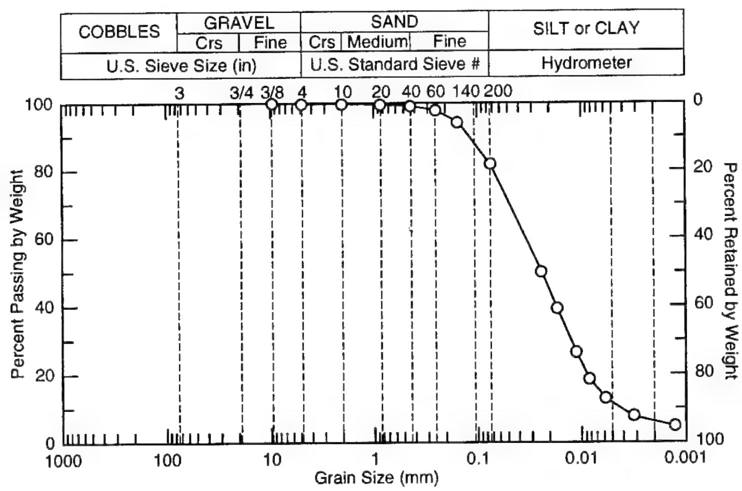
a. General construction.



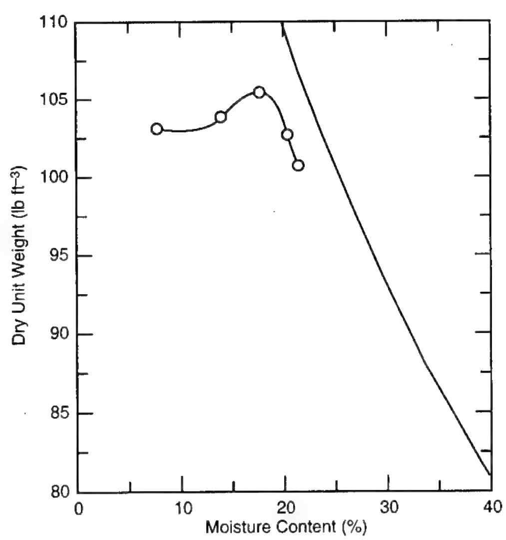
b. Bin liner (south side in foreground).

Figure 8. Experimental soil bin.

closed system, so the only water in the soil during the tests is that present at the start.



a. Grain size distribution (ASTM 1996a).



b. Proctor test results with 5.5-lb (2.5-kg) hammer (ASTM 1996b).

Figure 9. Silt used in tests.

Soil

The soil is a low-plasticity, inorganic clayey-silt, with 81.6% silt- and clay-sized particles and 17.7% fine sands (Fig. 9a) and is classified as ML in the Unified Soil Classification System. It has a specific gravity of 2.72, a liquid limit of 28%, and a plastic index of 1 (Shoop and Gatto 1992). The Proctor test shows that its maximum dry density is achieved at 17% gravimetric soil water content (Fig. 9b). The silt was wetted to a gravimetric water content of 21 to 23% (Table 2), which is 92 to 97% saturated to simulate a thawed, saturated silt at a cold, humid site in early spring, and placed into the bin.

We placed two to three backhoe buckets of soil in the bin, spreading each bucket load with a shovel and raking it level. When this loose soil was about 8 in. (20 cm) thick, we tamped it to a 6-in. (15-cm) soil layer and roughened the surface with a rake before the next backhoe load was placed to reduce the development of boundaries between the layers. Three soil layers were prepared in this fashion. Dry densities and volumetric water contents of the soil at the surface of each layer were 103–104 lb/ft^3 (1.64–1.67 Mg/m^3) and 35–38%, respectively (Table 2).

On the surface of the final soil layer, we formed a rectangular rill

Table 2. Initial conditions on the surface of each soil layer. Cores taken and calculations made by Richard Roberts, CRREL, 25 April 1995. Sample locations shown in Figure 13. Core size = 0.01 ft^3 = 283.2 cm^3.

	γ		γ_d				w	θ	s
Layer/core no.	*(lb/ft^3)*	*(Mg/m^3)*	*(lb/ft^3)*	*(Mg/m^3)*	e	n	(%)	(%)	(%)
1/BD1	127	2.03	104	1.66	0.63	0.39	22.7	37.6	97
2/BD2	126	2.01	103	1.64	0.65	0.39	22.3	36.4	92
3/BD3	126	2.02	104	1.67	0.62	0.38	21.2	35.2	92

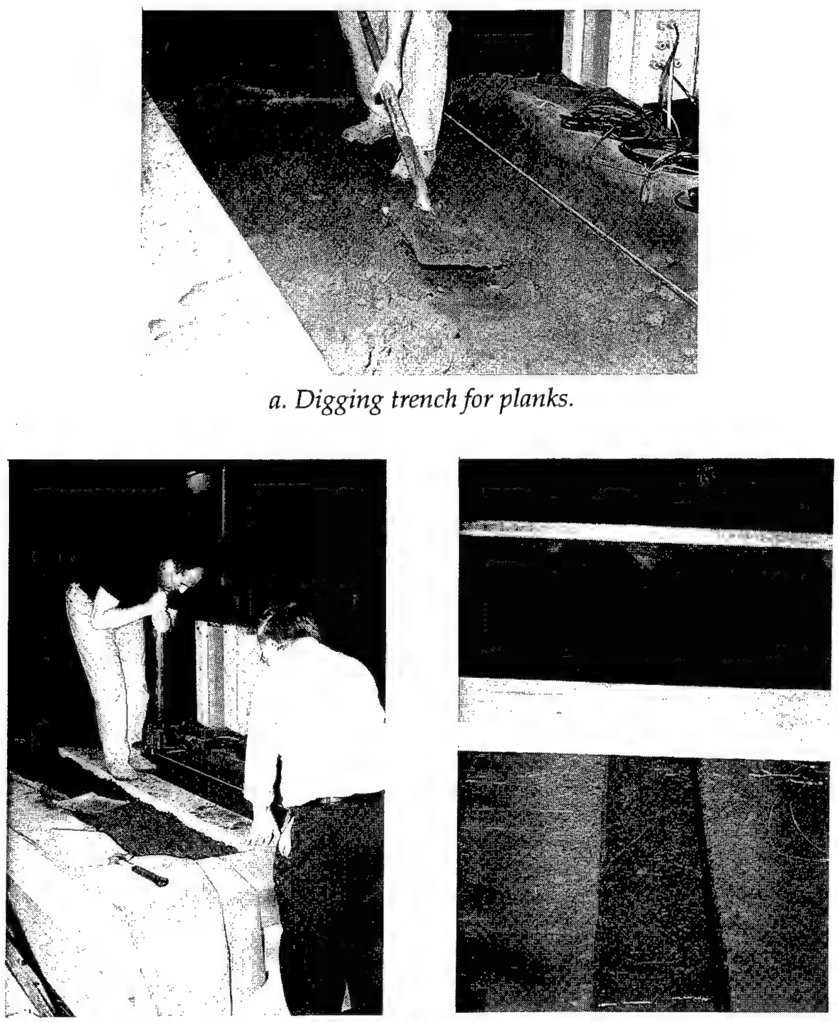
γ = moist unit weight (density)
γ_d = dry unit weight (density)
e = void ratio
s = saturation
n = porosity
w = gravimetric water content
θ = volumetric water content

by embedding two stacked 2- × 8-in. (5- × 20-cm) planks in the soil (Fig. 10). We dug a trench, placed the planks in the trench, backfilled around them, tamped them down and removed them before the first freeze.

Instrumentation and measurements

Soil freeze–thaw

I froze the soil by placing three refrigeration panels on the bin top and circulating the refrigerant through them (Fig. 11). The panels rested



a. Digging trench for planks.

b. Tamping planks into trench. *c. Simulated rill before F1.*

Figure 10. Preparation of simulated rill.

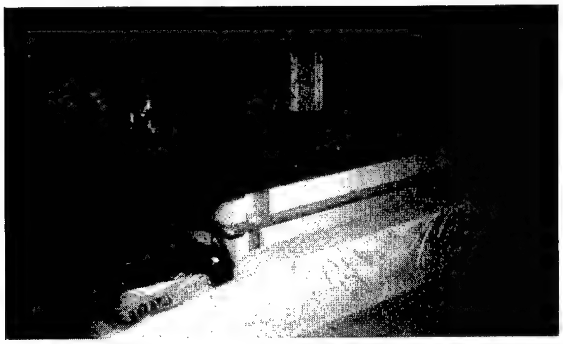


Figure 11. Soil bin, during a freeze, covered with panels and an insulating blanket.

creases dramatically (Atkins 1989). This marked change in resistance is a more reliable indication of the phase of soil water than soil temperature alone, because a soil can be 0°C when the water within its voids is still unfrozen (Atkins 1979).

When most of the soil water between a ring pair is frozen, the resistance recorded by that pair tends to level off until the soil begins to thaw, then the resistance drops just as rapidly as when it froze (Fig. 14). When thaw is complete, the resistance returns to a before-frost value. Thus, I determined the frost penetration rate in the bin from the resistance curves that showed the time when freezing began and when the frostline reached the depths of the successive ring pairs, which were at known depths.

Table 3. Measurements and instrumentation.

Condition	*Measurement*	*Instruments*	*Measurement accuracies*	*Measurement frequency*
0°C isotherm	Temperature (°C)	RG Thermocouples	± 0.1°C*	Hourly
Frost depth	Soil resistance (millivolts)	Resistivity gages	Absolute units not measured; change is important	Hourly
Soil surface geometry	Distance from datum to soil surface (mm)	Millimeter stick	+1 mm (est.)	Before and after freeze and during thaw
Soil water	Temperature-corrected dielectric constant; converted to % by volume	Hydra Probes†	± 0.015 to 0.020** ± 0.003††	Hourly

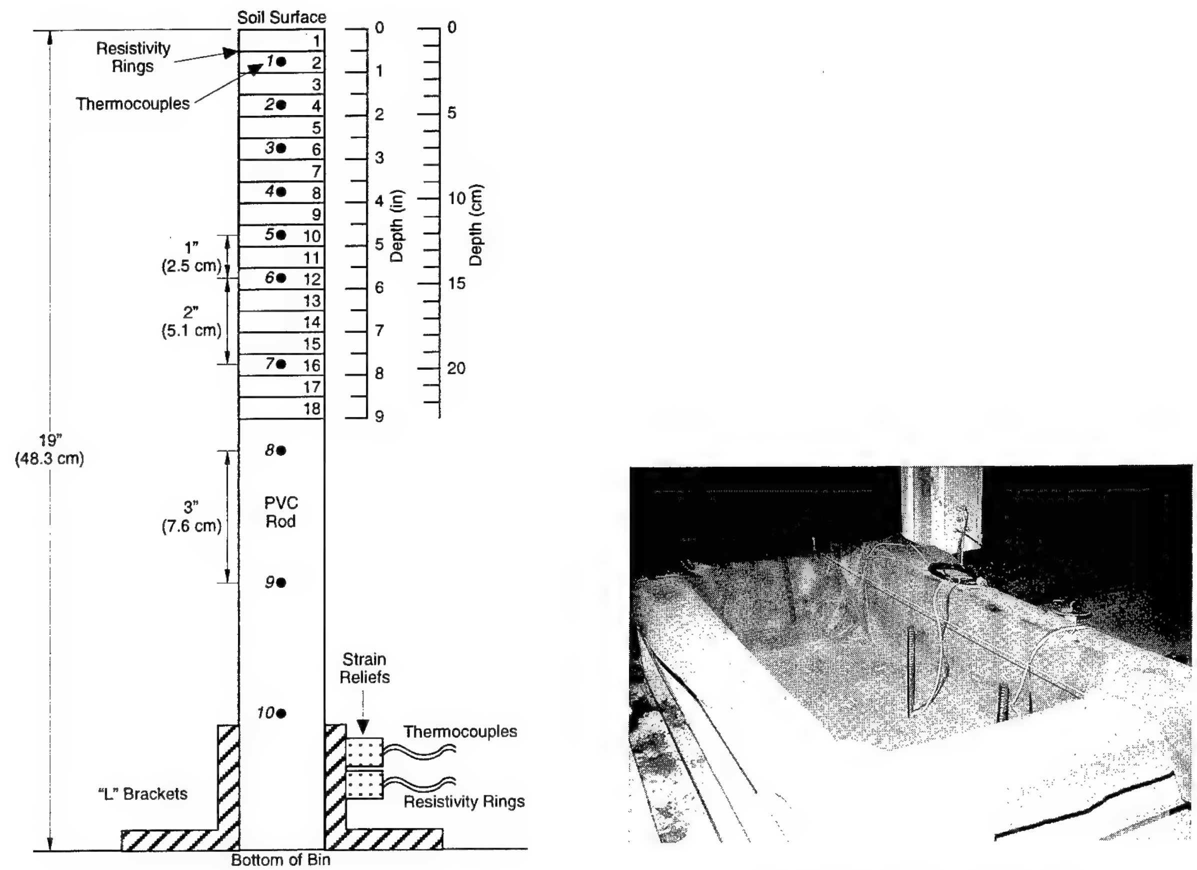
* Within temperature range of the experiment, –12 to 20°C.
† Vitel, Inc. (1994).
** Absolute accuracy with no soil-specific calibration performed.
†† Relative accuracy in the same soil.

about 5 in. (13 cm) above the soil surface and cooled the air between them and the soil. The freeze (F) portion of a FT cycle is the period when the bin air temperature (T_a) was 0°C or below. Thaw (T) began when the panels were removed and the bin soil was exposed to the ambient air; thaw ended when soil resistances showed that all frozen soil had melted.

Frost depth was measured by two Resistivity Gages (RG) (Table 3) constructed and installed according to Atkins' specifications (1979, 1990). Each gage consists of a PVC rod with 18 copper rings (Fig. 12) to measure soil resistance and 10 thermocouples to measure soil temperature. The RGs were mounted to the bottom of the bin (Fig. 12b); the final soil surface was even with the RG tops (Fig. 13). The RG measures soil resistance and, as the water in the soil between two rings on the rod freezes, the resistance of that soil in-

Four thermocouples measured the temperatures of the bottom of the panels (T_p), the air (T_a) between the panels and the soil surface, the soil surface next to RG C (T_{ssc}), and the soil surface in the middle of the rill (T_{ssr}) (Fig. 13). These thermocouples and those in the RGs were from the same manufactured wire lot, and four from that lot were calibrated in an ice bath to determine their absolute accuracy. Three sets of measurements were taken at 5-minute intervals while the bath was stirred. The 12 readings averaged –0.035°C, with a standard deviation of 0.032°C, and maximum and minimum readings were 0.027°C and –0.080°C respectively. Thus, all the thermocouple temperatures have an absolute accuracy of ± 0.1°C and a relative accuracy of 0.01°C.*

* Personal communication with K. Knuth, CRREL, 1995.



a. Schematic.

b. Gages mounted over bin liner.

Figure 12. Resistivity gages.

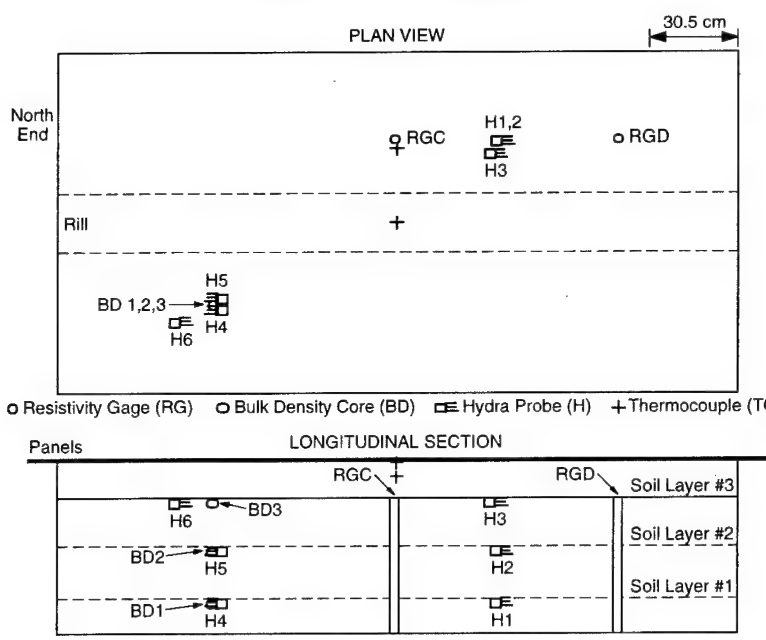


Figure 13. Instrument layout.

Water content

I monitored soil water redistribution during each FT cycle using six Hydra probes (Fig. 13). The probes measure a soil's high frequency (50 MHz) complex dielectric constant, which is made up of a capacitive and a conductive electrical response (Vitel, Inc. 1994). The capacitive part is most indicative of soil water content, while the conductive portion reflects predominantly soil salinity. As a soil gets wetter, the capacitive response increases and, with appropriate calibration, the dielectric constant measurement is directly related to soil water content. The probe also measures soil temperature with a calibrated thermistor in the probe head. The temperature is used to remove most of the temperature effects on soil dielectric constant when those data are converted to water content.

When we installed the probes, we placed soil around the tines (Fig. 15) to ensure good soil–tine contact, as recommended by the manufacturer. We dug two holes in the surface of each soil layer and placed one probe horizontally in each hole. The Hydra probes read from 35–37% volumetric soil water before the first freeze, which compares well to that determined from the bulk density cores (Table 2). The RGs, thermocouples, and Hydra probes were connected to Campbell dataloggers (Fig. 16) for data acquisition, storage, and relay through the FERF computer data collection system (Knuth 1989) to my computer.

Surface geometry

I used a millimeter stick to measure the vertical distances from an aluminum bar to the soil surface before and after each freeze and thaw. I aligned the stick with a vertical mark on the bar before each reading to ensure that I was measuring the true vertical distance to the soil surface (Fig. 17). As a check of accuracy, I measured a distance when the stick was 5° out of vertical. That measurement was 1 mm too long, but the 5° was obviously not vertical, so it was easy to hold the stick less than 5° out of vertical during each measurement. Thus, a conservative estimate of error for each measurement was +1 mm.

The bar was bolted in place above the soil at locations 1, 3, 5, and 7 (Fig. 17b). The vertical distances were measured from stations 5 cm apart horizontally along the bar, except over the rill, where the stations had to be closer together to adequately define the rill's cross-sectional shape. Frost heave after each freeze was determined from the vertical distance at four out-of-rill stations and two in-rill stations per location. The distances were also used to construct rill profiles from which the rill hydraulic radius was determined. I originally planned to measure all seven profiles (Fig. 17a) with an automatic acoustic profiler. However, the profiler did not work properly across the rill's sloping sides, so I had to measure the profiles by hand and only did four.

RESULTS AND DISCUSSION

FT Cycle 1

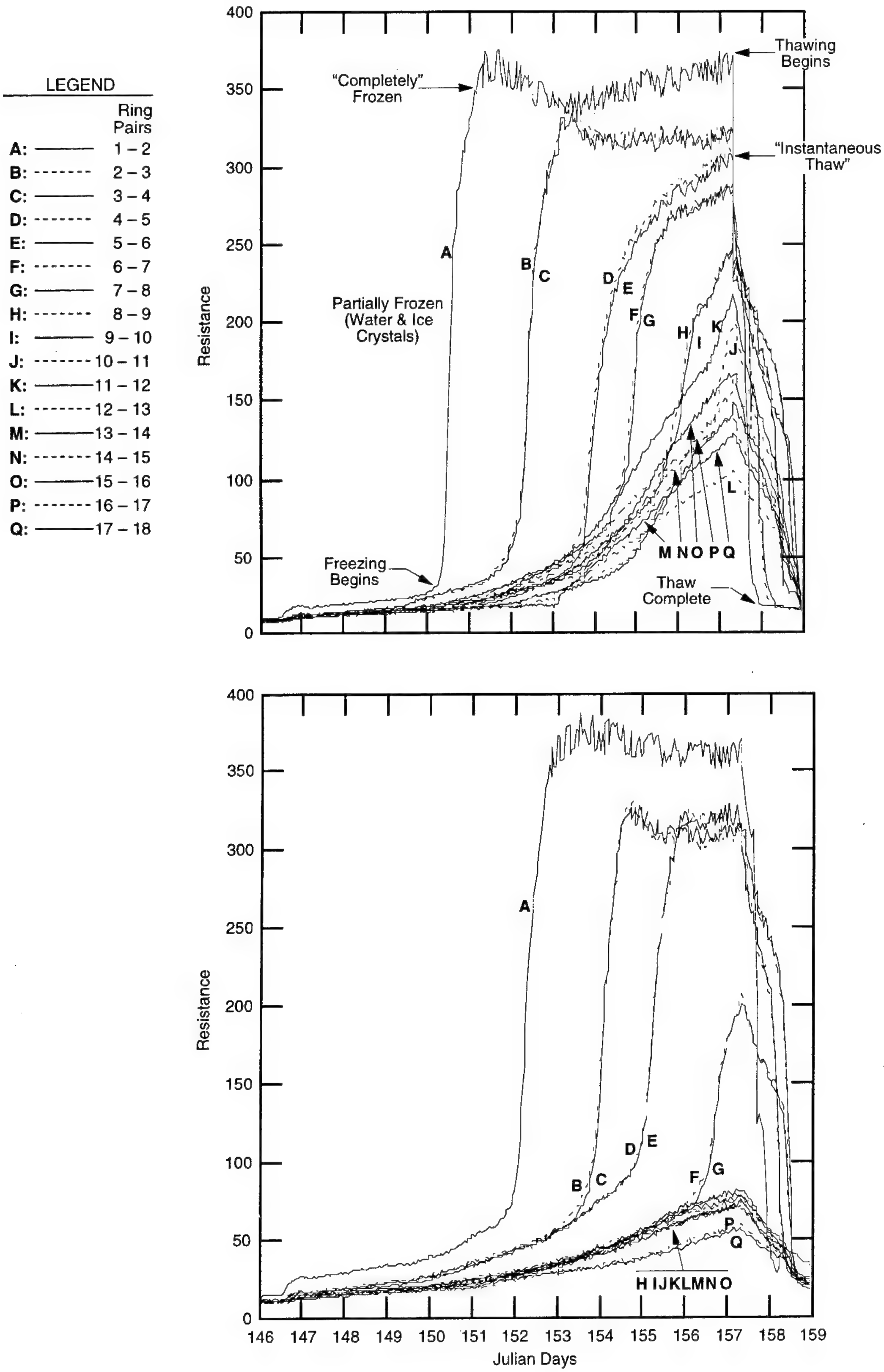
Frost formation and thaw

The panel temperature (T_p) was lowered to –20 to –30°C at 1400 hours on Julian day 146 (146.14) for about 11 hours and was held between –8 to –10°C (Fig. 18). The first freeze (F1) began at 147.15 when T_a reached 0°C and ended 233 hours later when the panels were removed at 157.08. The soil surface at RG C reached 0°C 35 hours (149.02) after F1 began (Fig. 18). The 0°C isotherm penetrated to a depth of about 6 in. (15 cm) at RG C during F1 (Fig. 19), an average of 0.04 in./hr (0.10 cm/hr) (Fig. 20a). The isotherm penetrated to about 5 in. (13 cm) at RG D (Fig. 19), an average of 0.03 in./hr (0.08 cm/hr) at RG D (Fig. 20b), while the frostline penetration rate averaged 0.03 in./hr at both gages (Fig. 20a,b). The first thaw (T1) was complete at 158.23 at RG C and at 158.15 at RG D (Fig. 14), 39 and 31 hours, respectively, after the panels were removed.

The liquid water decreased dramatically in the surface soil as most of the water froze, but only a small decrease occurred at depths of 7 in. (18 cm) and greater (Fig. 21) as soil water was drawn to the freezing front. During F1, the liquid water at these depths never froze. The similar changes in the distribution of soil water diagonally across the bin (Fig. 13) suggest that they represent the soil water movement out of the rill throughout the bin. Differences in the heave between the out-of-rill and in-rill stations suggest that soil water movement under the rill may have been different.

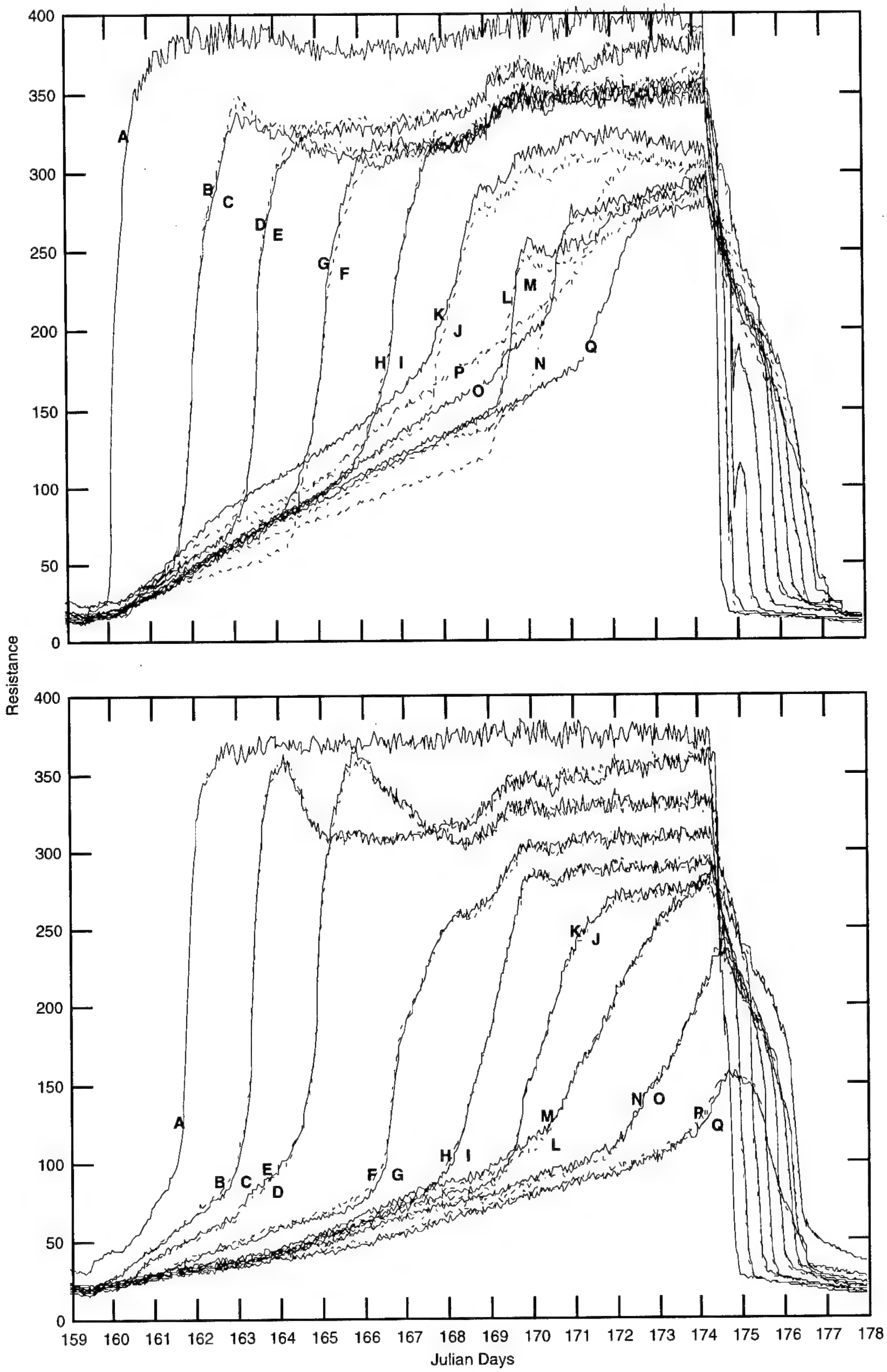
Rill hydraulic geometry

The soil outside the rill heaved at all 16 measurement stations an average of 1.5 cm during F1 (Table 4), and the difference between maximum and minimum heave was 1.4 cm. Soil in the rill bottom heaved at six of eight stations by an average of 0.4 cm and the difference between maximum and minimum heave was 1.2 cm, which is less than the soil outside the rill. This is some-



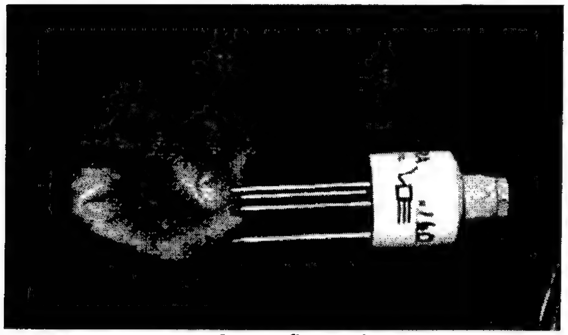
a. FTC1.

Figure 14. Soil resistances (top—RGC; bottom—RGD).

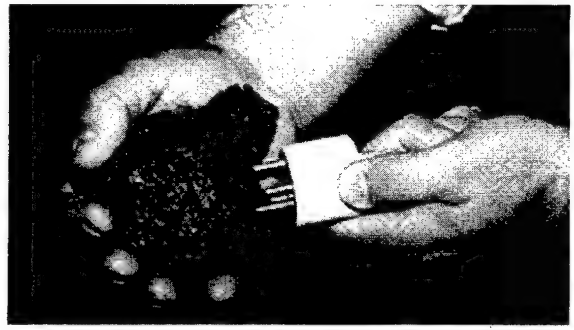


b. FTC2.

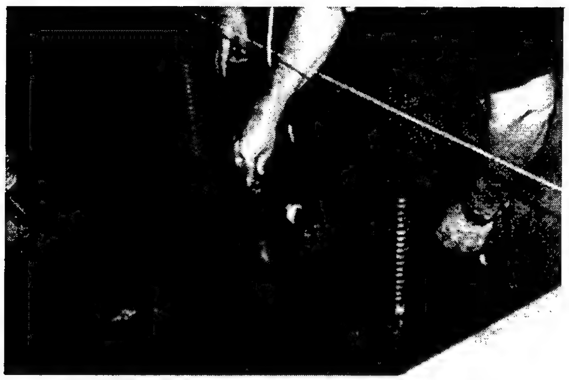
Figure 14 (cont'd).



a. Probe configuration



b. Soil placement around probe

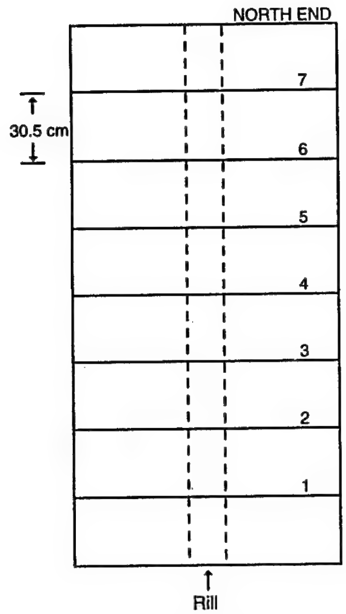


c. Probe burial.

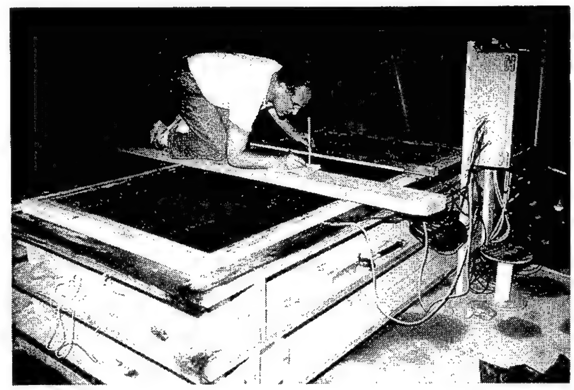
d. Probe in position.

Figure 15. Hydra probe.

Figure 16. Instruments connected to FERF data collection system.



a. Profile locations.



b. Measurements along profiles.

Figure 17. Soil surface geometry measurements.

Table 4. Frost heave (cm). Out-of-rill measurements were made at stations 105, 90, 30, and 15 on profiles 1 (P1), 3, 5, and 7. In-rill measurements were made at stations 65 and 55 on the same profiles.

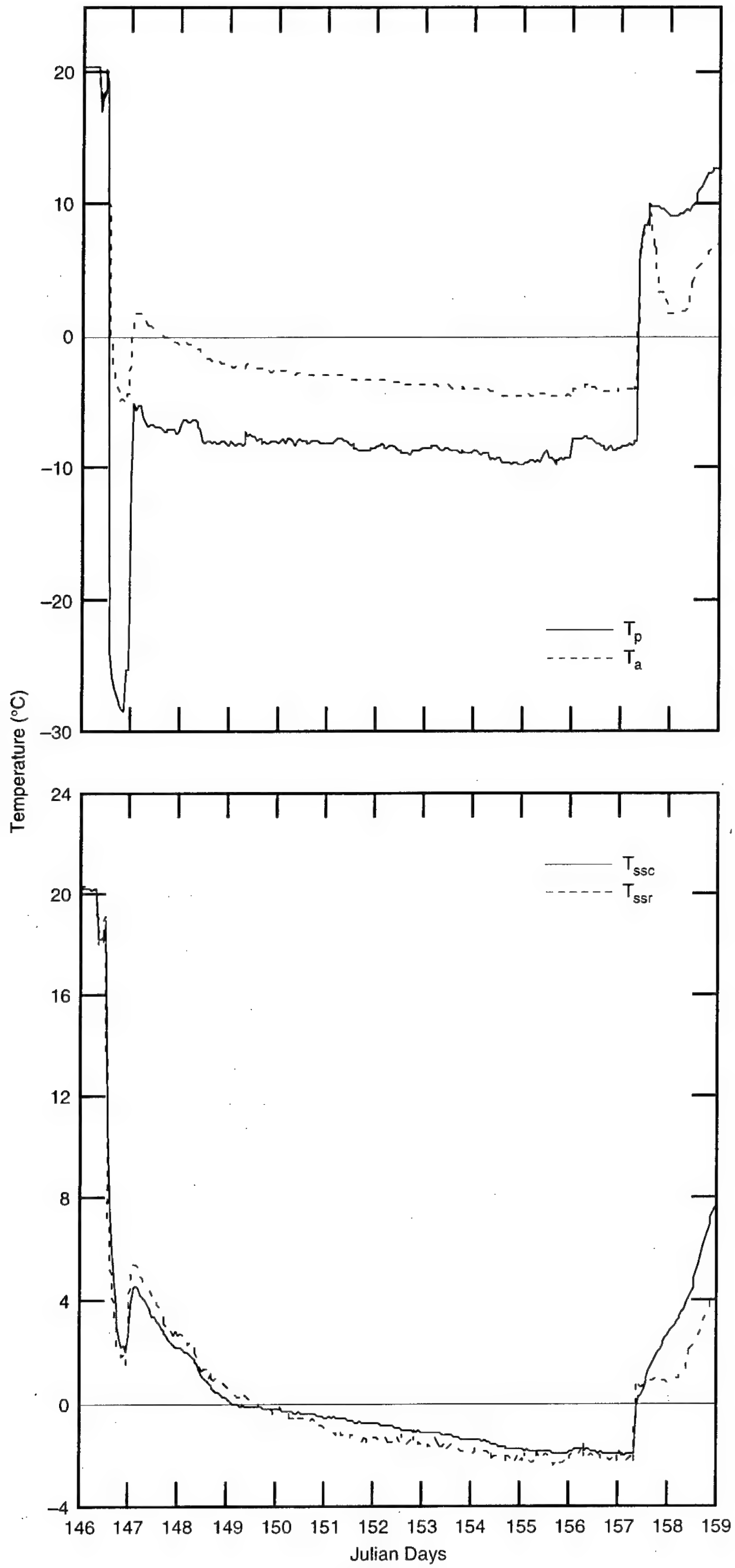
	Out of Rill (n = 16)			*In Rill (n = 8)*		
	Max.	*Min.*	*Avg.*	*Max.*	*Min.*	*Avg.*
F1	2.2 (P3)	0.8 (P7)	1.5	1.2 (P3	0 (P1,7)	0.4
F2	3.1 (P5)	1.8 (P1)	2.5	2.2 (P5)	0.8 (P1)	1.4

what surprising in that T_{ssr} was usually 0.1 to 0.6°C lower than T_{ssc} (Fig. 18) and I would have expected that this lower temperature would have established a steeper temperature gradient below the rill, causing more soil water movement to the freezing zone under the rill, resulting in greater in-rill heave.

The rill profiles measured 2 hours before F1 and 30 minutes after T1 began (Fig. 22a,b) show that the frozen rill sidewalls were generally nearer to vertical than before they were frozen, which suggests that the soil along the rill wall near the crests heaved more than that near the rill bottom. Heat loss from the soil near the rill crest may be enhanced because of the two surfaces through which the heat can flow to the air. Consequently, more soil water could have been drawn to the rill crest and frozen.

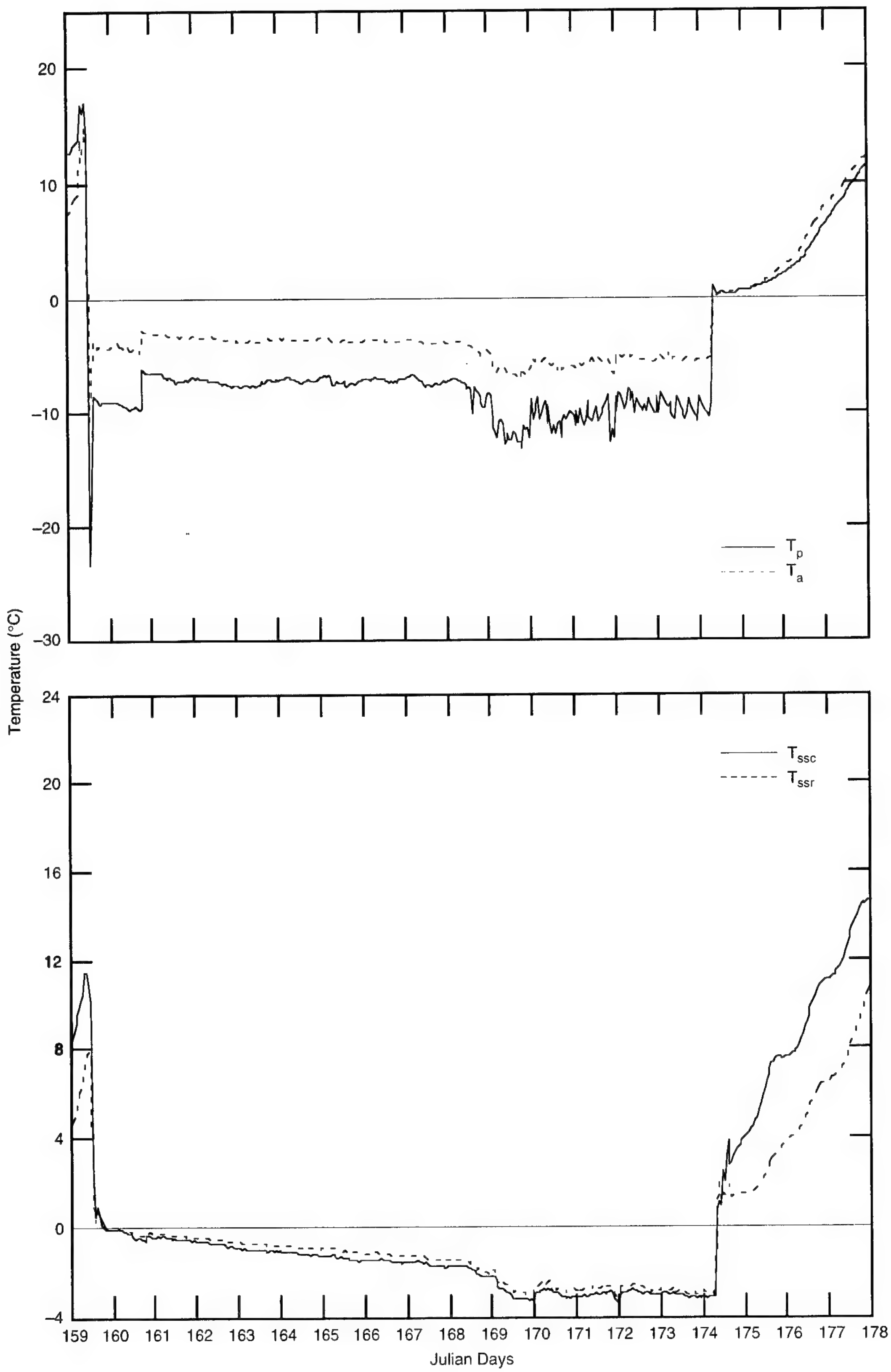
The degree of FT-induced rill side slope slumping would be directly related to the amount of soil water that's drawn into the freezing zone as frost penetrates into the soil. The amount of frost heave is a measure of the amount of ice in the frozen soil, which is determined by the amount of additional water drawn to the freezing soil, which in turn is determined by the temperature gradient in the soil and the amount of available soil water. Upon thaw, the additional soil water tends to saturate surface soils, making them susceptible to soil flows and slumps. Ice lenses in the surface soil and scattered needle ice, 0.1–1.0 cm long, on the soil were visible at the end of F1 and F2, which suggests that sufficient water had been drawn into the freezing soil to saturate the surface soils when thaw began.

Water was added to the surface soil at the end of each freeze. Before the panels were removed, warm refrigerant was circulated through them. Otherwise, cold refrigerant warming in the panels would expand and rupture them. When the panels heat up, the needle ice that forms on their undersides during a freeze (Fig. 23a) partially melts, and slush ice and meltwater fall onto the soil (Fig. 23b, 24a). This additional water (I did not measure its volume) would simulate a storm of very wet snow falling on a frozen soil surface and the degree of saturation of the surface soil as it starts to thaw would likely be comparable to that which may be found in the field



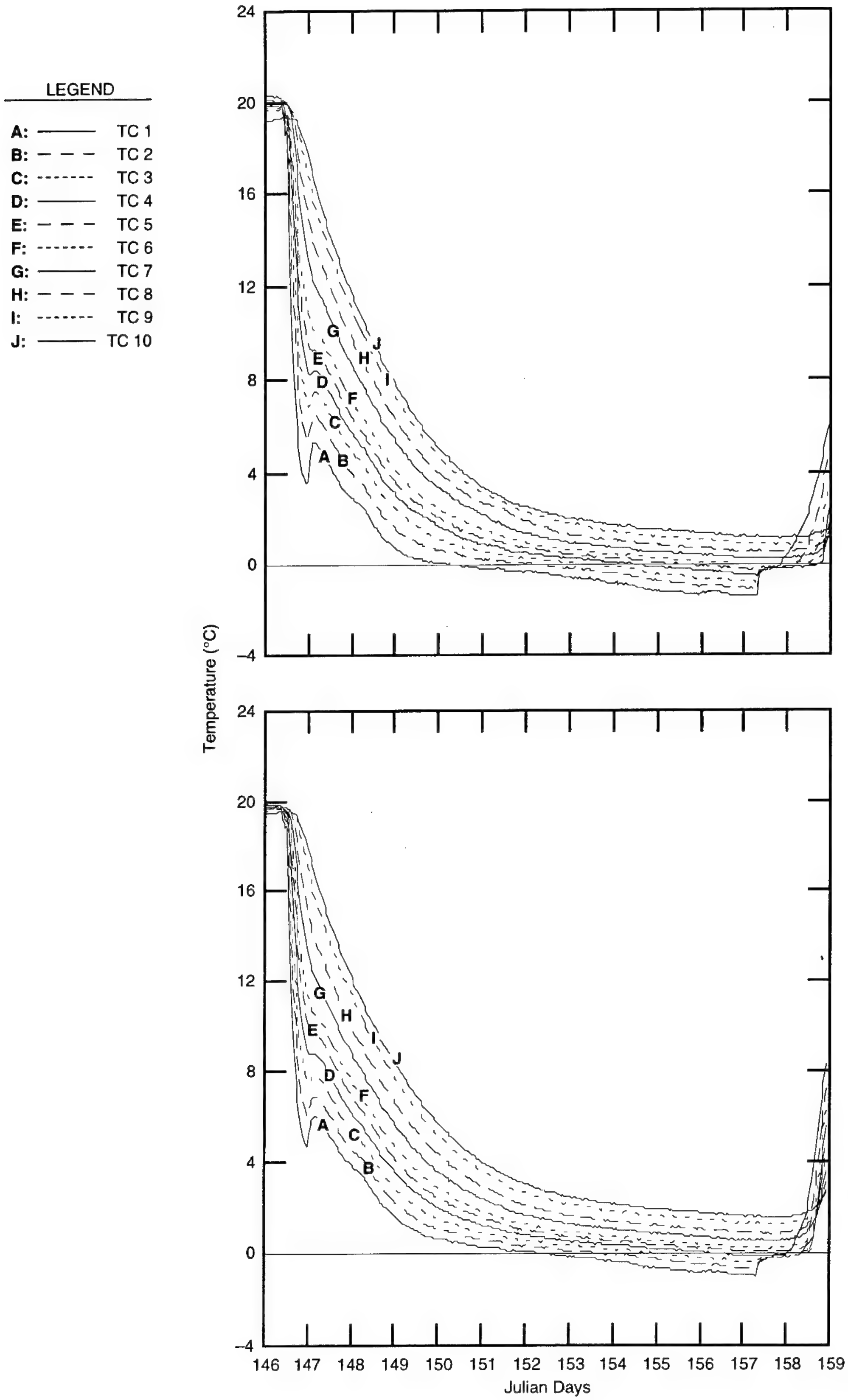
a. FTC1.

Figure 18. Temperatures of the panel (T_p), air (T_a), soil surface at mid-rill (T_{ssr}), and soil surface next to RG C (T_{ssc}).



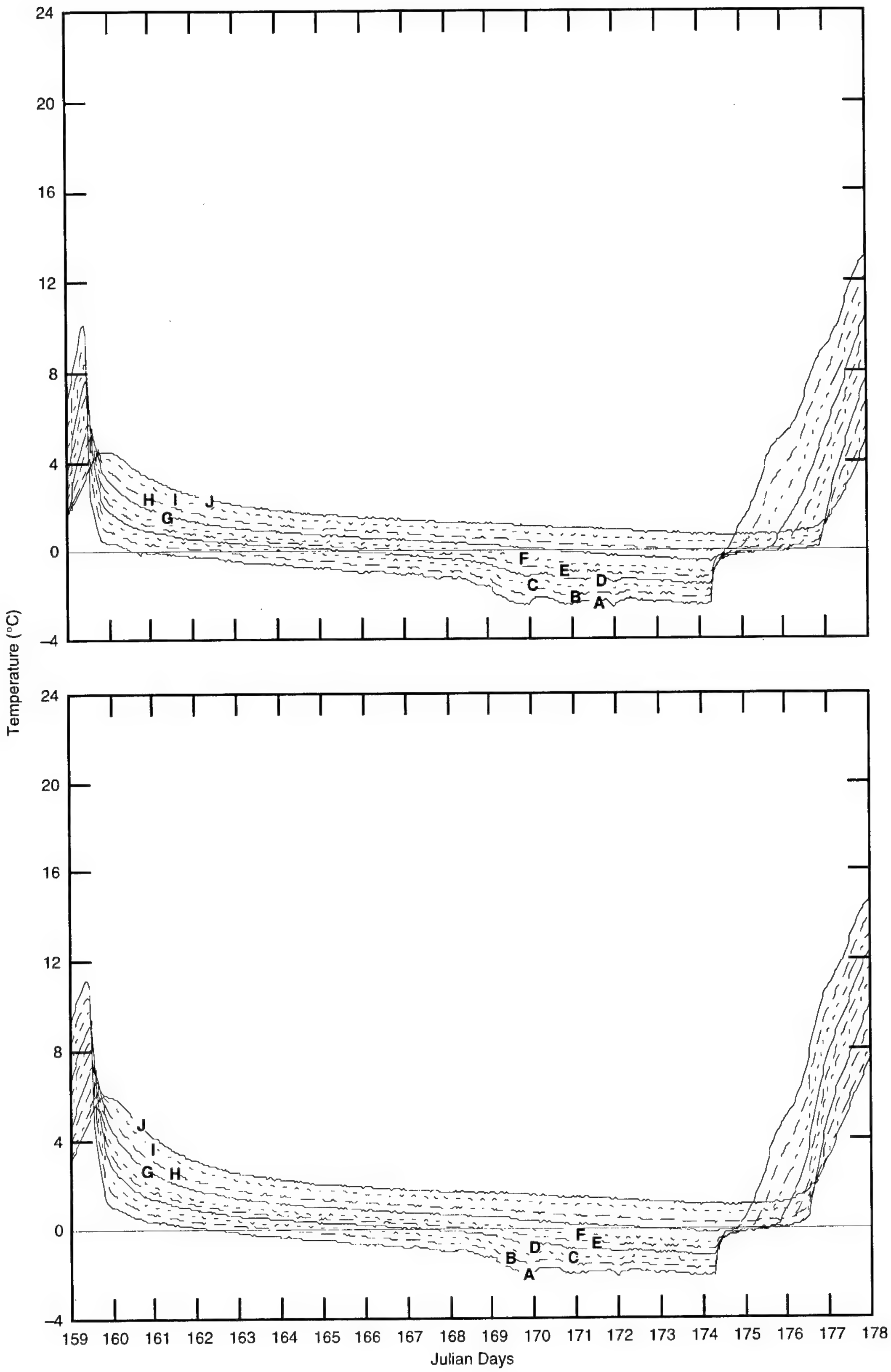
b. FTC2.

Figure 18 (cont'd).



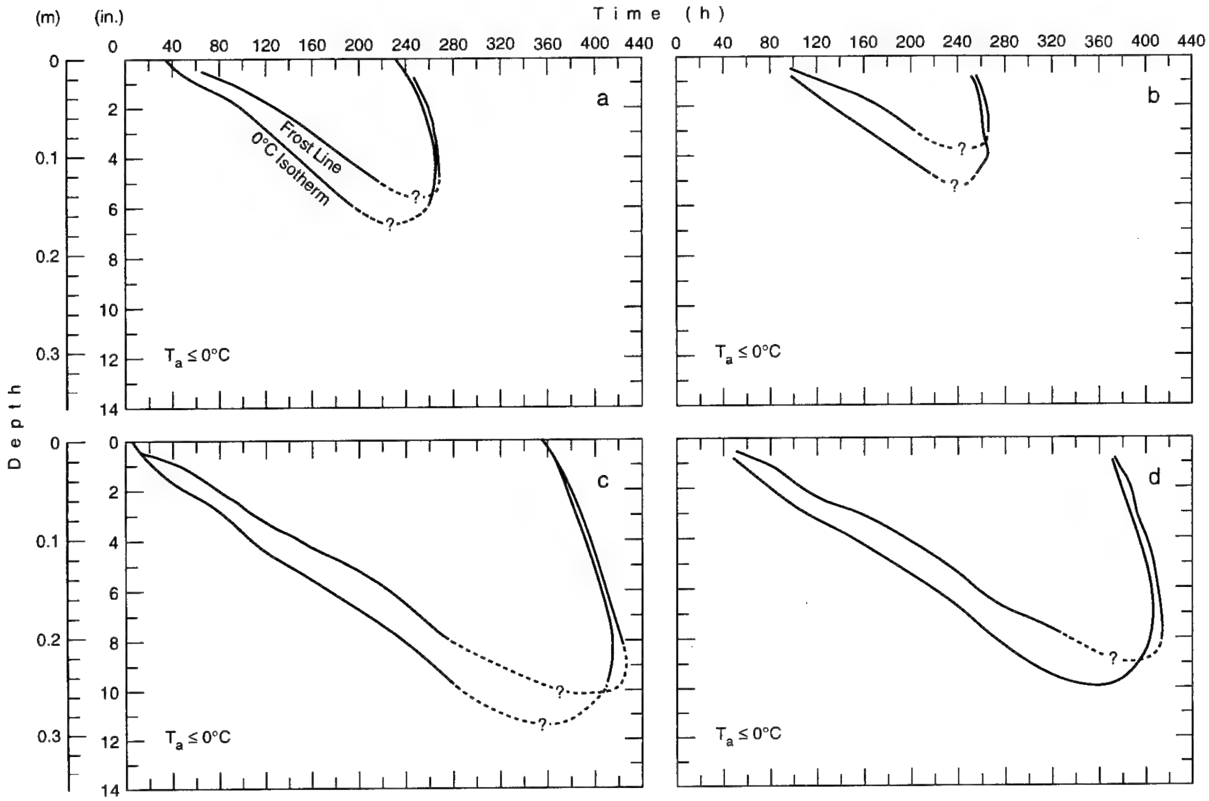
a. FTC1.

Figure 19. Subsurface soil temperatures (top—RGC; bottom—RGD).



b. FTC2.

Figure 19 (cont'd).



a—RG C, FTC1; b—RG D, FTC1; c—RG C, FTC2; d—RG D, FTC2.

Figure 20. Frost penetration and thaw in soil bin.

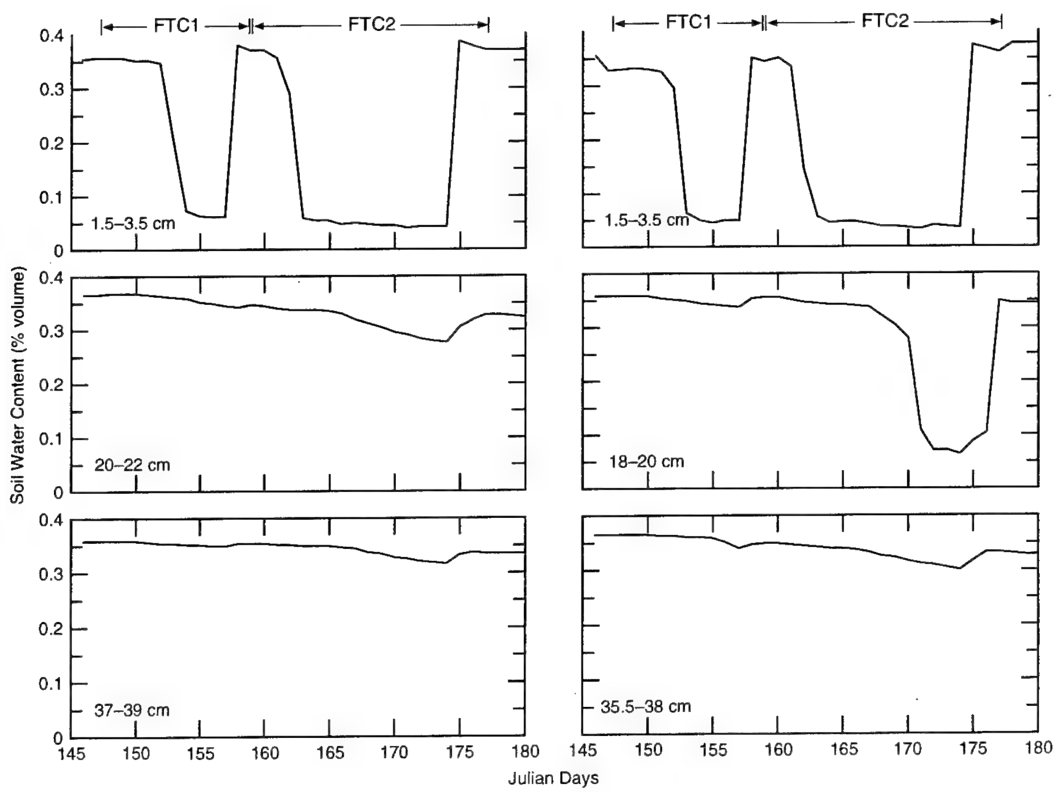
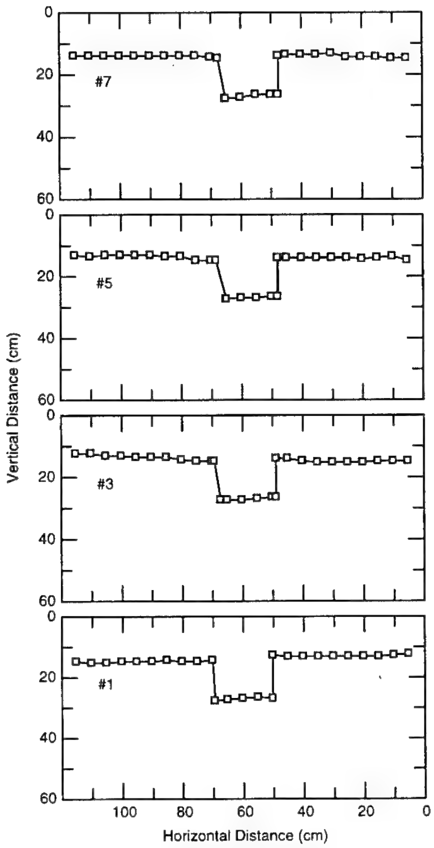
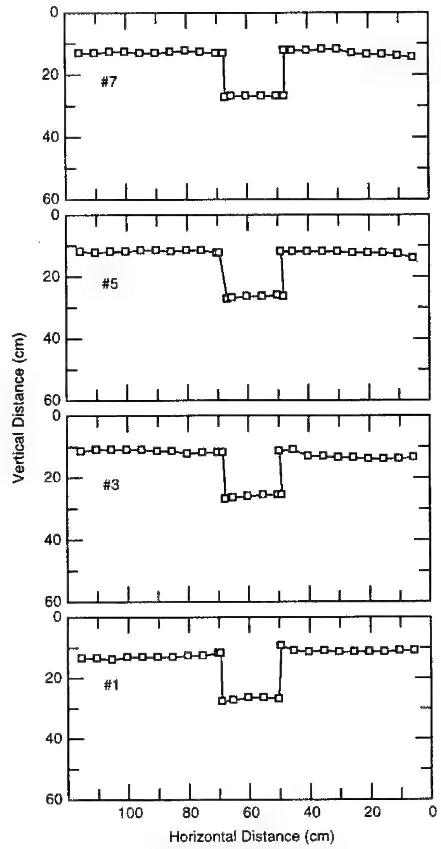


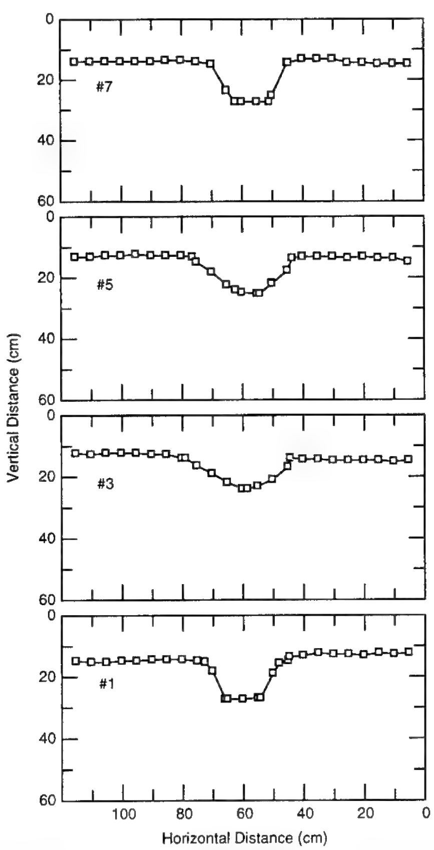
Figure 21. Volumetric soil water (%) measured by the Hydra probes at 0600 each day.



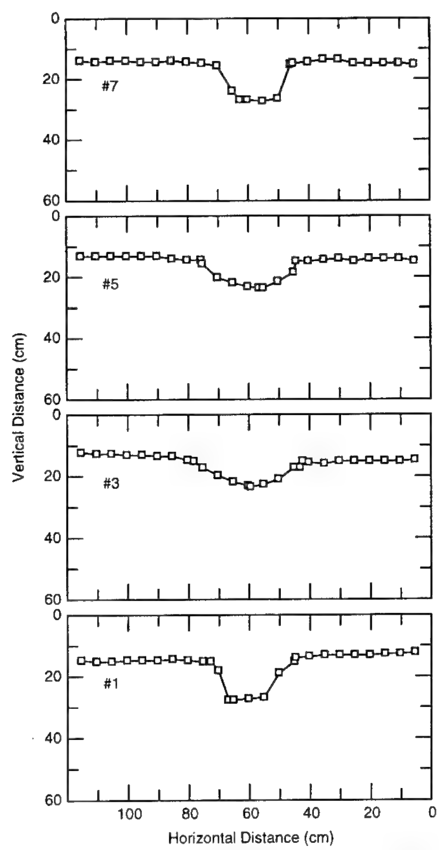
a. 2 hours before F1.



b. 30 minutes after T1 began.

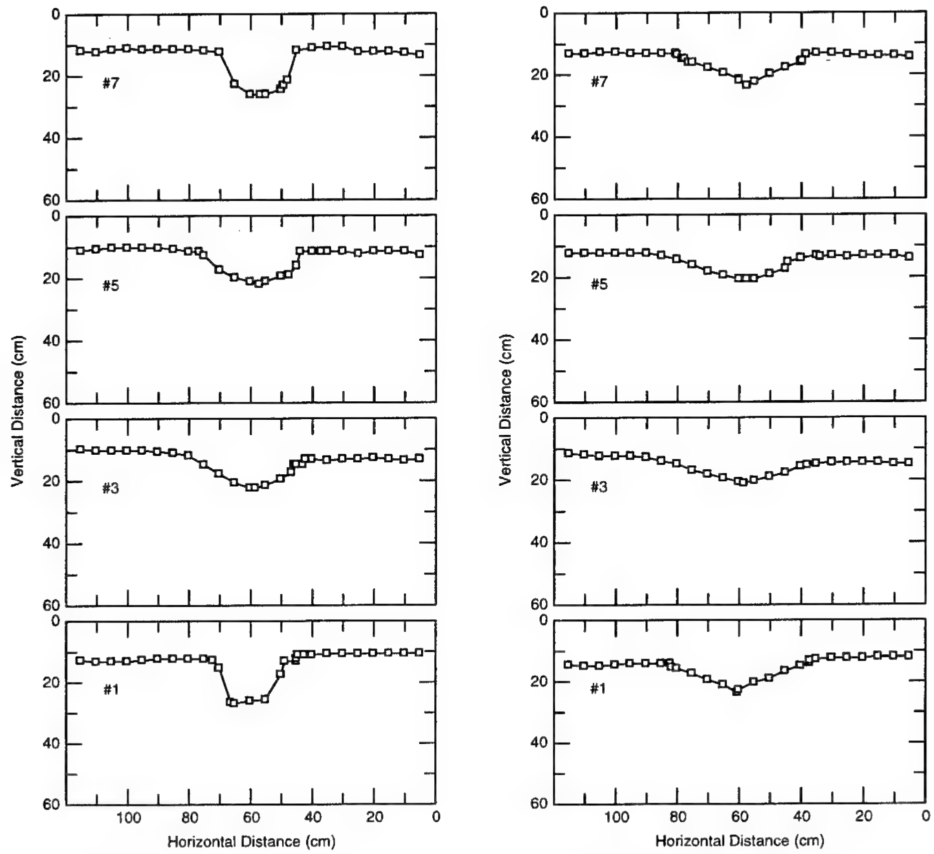


c. 26.3 hours after T1 began.



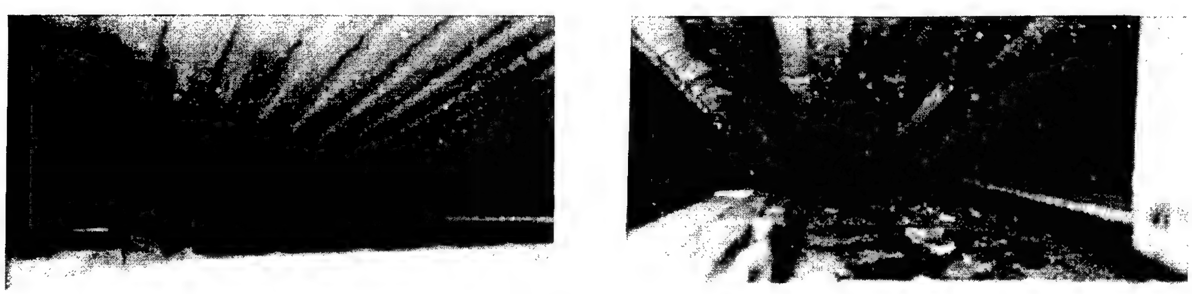
d. 49 hours after T1 began; 3 hours before F2.

Figure 22. Rill profiles.



e. 20 minutes after T2 began. *f. 6.3 days after T2 began.*

Figure 22 (cont'd). Rill profiles.



a. Needle ice on panels before thaw. *b. Melting needle ice*

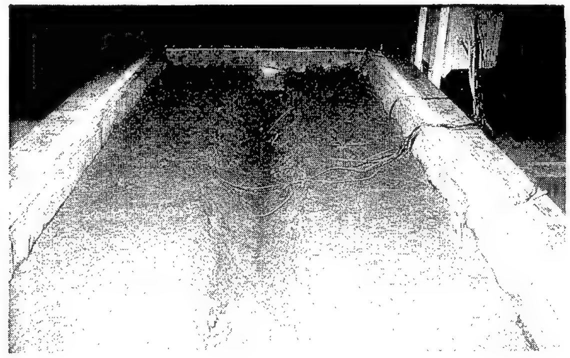
Figure 23. Underside of panels at the end of a freeze.

very early during spring thaw in a temperate climate.

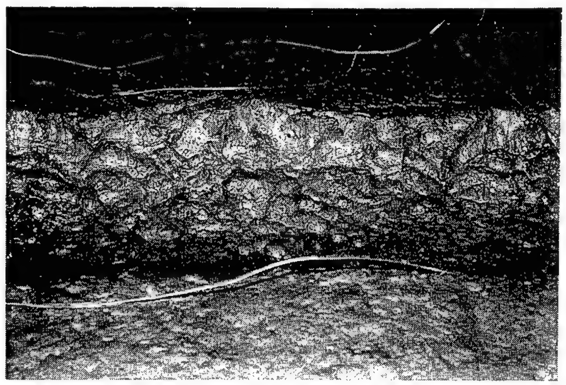
Some of the scattered standing water on the soil surface at the beginning of T1 slowly drained into the thawing soil, contributing to its instability, and some flowed over the rill crest, transporting sediment into the rill. In some locations, the saturated soil adjacent to, but outside of, the rill flowed over the rill crest into it, forming microdrainage channels about 1 mm deep along the rill sidewalls.

As thaw continued, the saturated sidewall soil flowed and slid down the rill in variably sized soil masses (Fig. 24c) along its entire length, although especially in mid-rill (Fig. 24b). Tension cracks along the rill crests (Fig. 24b) define the blocks of soil that had begun to slide. The more dramatic cross-sectional changes resulting from the rill soil failures occurred at profiles 3 and 5 (Fig. 22c and d) in the middle of the bin, rather than at profiles 1 and 7 near the bin walls where freezing was less intense.

a. 30 minutes; note slush from panels on soil surface.



b. 31 hours; note slumped sidewalls, especially in mid-rill.



These changes in the hydraulic geometry of the rill are the main aspect of the experiment because they affect the hydraulic radius, *R*, of the rill, which would partially determine the velocity and, thus, the erosivity of subsequent flows in the rill. The rill *R* before F1 at the four profile locations averaged about 5.5 cm (Fig. 25, Table 5). After T1, it changed insignificantly at profiles 1 and 7 and decreased by about 33% at profiles 3 and 5. Such a reduction in *R* would cause the vel-

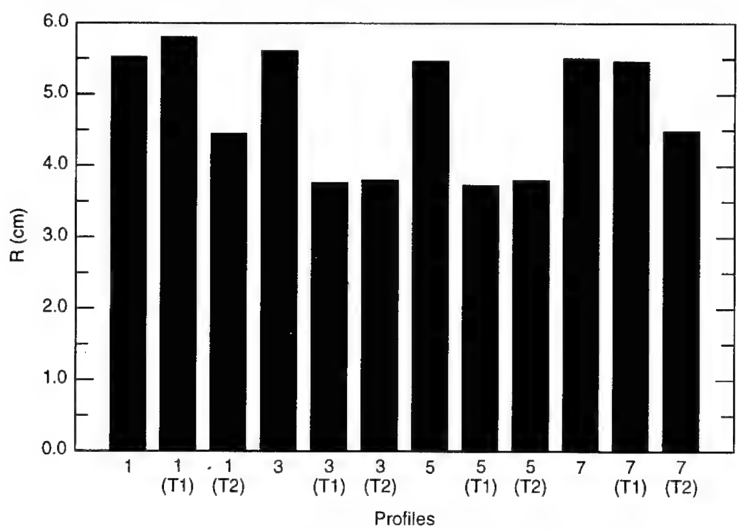


Figure 25. Hydraulic radius, R, *after T1 and T2.*

Table 5. Rill hydraulic geometry measurements.

	Profile	Bottom width (cm)	Top width (cm)	Depth (cm)	P (cm)	A (cm^2)	R (cm)
	1	19.0	19.9	13.2	46.7	257.5	5.5
T1	1	11.8	27.9	12.4	42.3	246.1	5.8
T2	1	0	44.6	10.4	52.4	231.4	4.4
	3	18.1	20.2	12.7	43.5	242.7	5.6
T1	3	0	35.7	8.6	41.2	154.3	3.7
T2	3	0	64.5	7.8	66.0	250.8	3.8
	5	16.7	20.2	12.7	42.6	233.6	5.5
T1	5	0	31.1	9.2	38.6	143.3	3.7
T2	5	0	54.7	8.1	58.2	220.6	3.8
	7	17.3	19.9	12.7	42.9	235.4	5.5
T1	7	11.5	24.8	11.5	38.3	209.0	5.5
T2	7	0	41.8	10.4	48.7	216.5	4.4

ocity of a bankfull flow to decrease by 24% using Manning's equation (eq 2) when keeping rill slope (S) and roughness (n) constant. Thus, in this hypothetical example, the erosivity of such a flow in that rill could decrease significantly after one FT cycle.

FT Cycle 2

Frost formation and thaw

The T_p was lowered and maintained between −7 and −13°C (Fig. 18). The second freeze (F2) began at 159.13 when T_a reached 0°C; T_a remained between −4 and −6°C until 174.08 (355 hours later) when I removed the panels to begin T2. The soil surface at RG C reached 0°C at 159.18 (Fig. 18b) and the 0°C isotherm penetrated to a depth of about 10 in. (25 cm) at both RGs, an average of 0.03 in./hr (0.08 cm/hr) (Fig. 20c and d). The frostline penetration rate averaged 0.03 in./hr at both RGs, as well (Fig. 20c and d). T2 was complete at 177.09 at RG C and at 176.16 at RG D (Fig. 14), 73 and 56 hours, respectively, after the panels were removed. The soil at RG C froze deeper and more completely than that at RG D and, thus, took longer to thaw.

Rill hydraulic geometry

F2 lasted 122 hours longer than F1, and the T_a during F2 was generally 1 to 2°C lower, causing more water to migrate to the freezing front, which resulted in more liquid water in the surface soil being frozen longer during F2 (Fig. 21). All stations in and out of the rill heaved and the amount of heave was greater during F2 (Table 4) because of this additional frozen water. The out-of-rill soil heaved more than in-rill soil, just as during F1. The temperature of the soil surface at RG C was generally 0.1 to 0.3°C lower than that in mid-rill during F2 (a reversal of that measured during F1), and possibly the temperature gradient in the out-of-rill soil was greater.

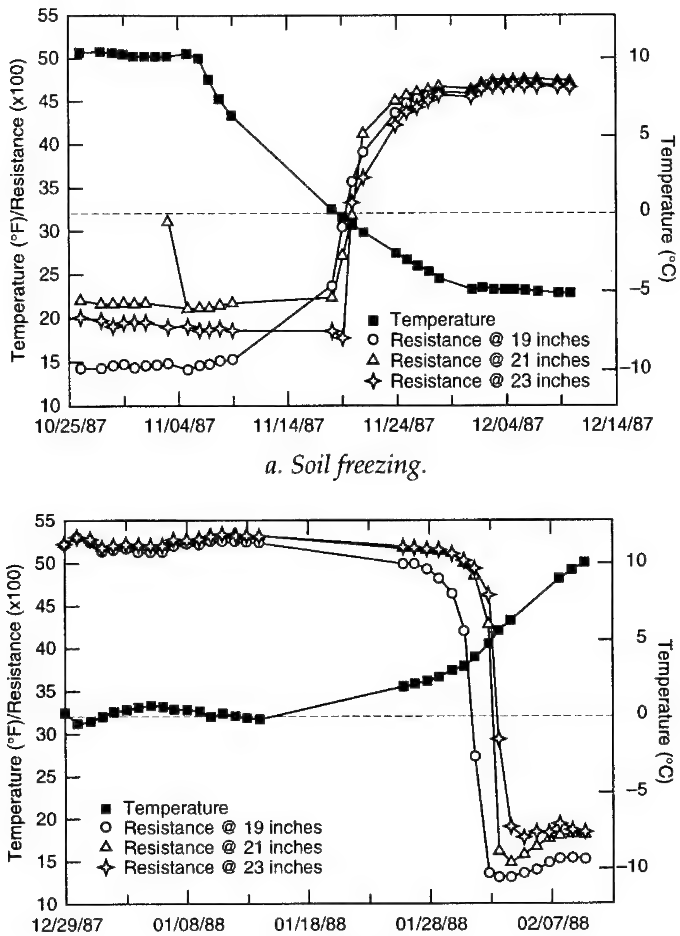
During F2 the in-rill and out-of-rill soil surfaces remained unchanged at profiles 3 and 5 (Fig. 22d and e) and there were minor changes at profiles 1 and 7. After 6 hours of thawing, however, substantial side slope collapse had occurred and the rill was significantly wider and shallower (compare Fig. 24b and 26). Some 6 days after T2 began, the rill had filled in significantly (Fig. 22f) and the changes at profiles 3 and 5 were greater than after T1 (Fig. 22d).

Figure 26. Rill shape 6-7 hours after T2 began.

The R at profiles 1 and 7 decreased 24 and 20%, respectively, after T2 (Fig. 25), while the R at profiles 3 and 5 was virtually unchanged. These decreases in rill R would reduce a hypothetical bankfull flow velocity by 17 and 14%, respectively. F2 lasted long enough to cause the near-wall parts of the rill to freeze sufficiently that there was substantial soil collapse there during thaw. Note the less dramatic shape changes at profiles 3 and 5 during F2. In regard to FT-induced changes in soil, numerous others (Chamberlain 1973, 1981; Akram and Kemper 1979; Formanek et al. 1984; Yong et al. 1985; Van Klaveren 1987; Benoit and Voorhees 1990; Othman and Benson 1993) have noted that the most dramatic change occurs after one FT cycle, with lesser change following subsequent cycles.

LESSONS LEARNED

Rings 1 and 2 on the RGs responded appropriately as a pair, but the others responded two pairs at a time rather than one pair at a time (Fig. 14). Two ring pairs should not respond together because the freezing front penetrated at 0.03 in./hr



a. Soil freezing.

b. Soil thawing.

Figure 27. Soil resistance changes in silt. (After Atkins 1989.)

(0.08 cm/hr), much less than the 0.5 in./hr (1.3 cm/hr) required for the frost to penetrate between two ring pairs in 1 hour (the time between samples). Knuth* reported that this erroneous response was likely caused by a capacitance problem in the cable leading from the RGs. I used the data from only one of the paired ring pairs, which reduced the resolution for locating the frost line from 0.5 to 1.0 in. (1.3 to 2.5 cm) for these tests. Future tests will be run with the RGs wired differently to avoid this problem.

Atkins (1989, 1990) points out that the general shape of the temperature and resistance curves during freeze and thaw should be similar (Fig. 27). However, Figures 14 and 19 show a precipitous drop in soil resistance and an instantaneous rise in temperature at the very beginning of T1 and T2. Obviously, ice in the soil does not thaw as quickly as these figures suggest. The problem was that the meltwater that falls onto the soil when the panels are heated seeped down between the RGs and the soil to a depth of 4 to 6 in. (10 to 15 cm). The rings and thermocouples then measure the resistance and temperature of this water. Atkins (1989, 1990) discusses the problem of water seepage around an RG and suggests burying the RG so that its top is 6 in. (15 cm) below the soil surface. However, I need to measure frost penetration down from the soil surface, so in future tests I plan to cover the top of the RGs with plastic before removing the panels to keep the meltwater away from them.

Freeze at RG D was less intense than at RG C (Fig. 20). RG C is located near two walls. Maximum heave always occurred at profiles 3 and 5 in the middle of the bin, the minimum always at 1 and 7 nearer the walls, and more soil water froze in the middle of the bin than nearer a corner. Heat penetration into the bin may have been greater nearer the bin corners because of the proximity to the two walls. Profile measurements during fol-

* Personal communication, 1995.

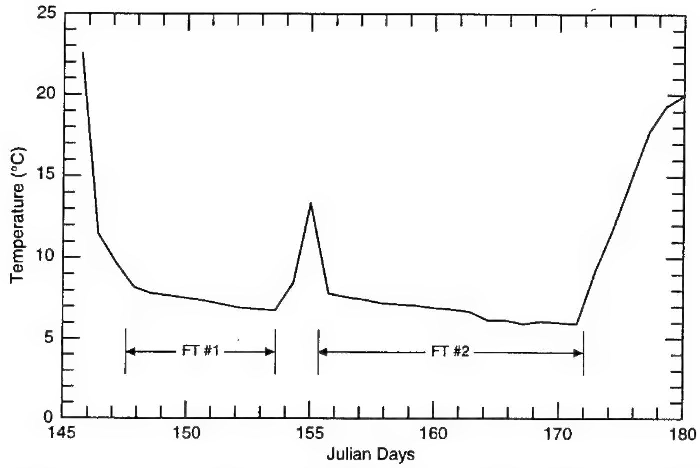
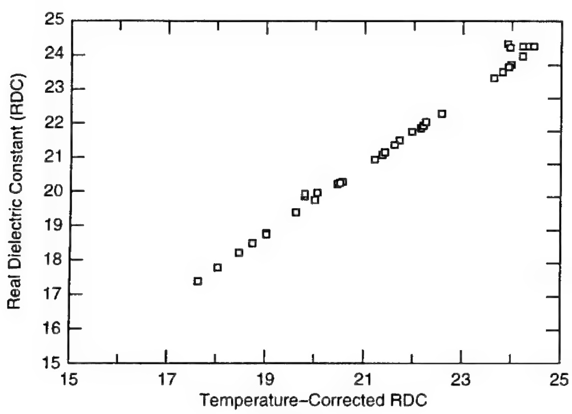


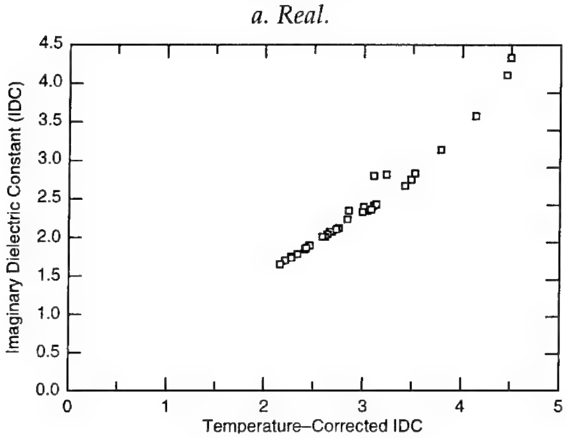
Figure 28. Soil temperature measured by Hydra probe 3 at 0600 each day when soil was frozen.

low-on experiments will be made exclusively in the middle portion of the bin soil.

The absolute values for Hydra probe soil water contents were inaccurate once a freeze began. The probe uses the soil temperature it records to calculate a temperature-corrected real dielectric constant of the soil (Vitel, Inc. 1994). This constant gives the water content. However, the probes were wired so that they'd switch off and on to take readings, but the switch failed and the probes remained on. The probes then heated up, which warmed the soil around them, and the temperature they recorded was incorrect. Probe 3 in the surface soil between RGs C and D (Fig. 13) measured 6–8°C above freezing (Fig. 28) when the surface soil here was frozen. However, the relative values for soil water are likely accurate because the real dielectric constants vs. the temperature-corrected constants recorded during these tests are closely correlated (Fig. 29). The switch problem in the Hydra probe circuits will be corrected* before the next experiments.



a. Real.



b. Imaginary.

Figure 29. Dielectric constants vs. temperature-corrected constants.

CONCLUSIONS

These initial tests suggest that the pattern of rill change attributable to FT-induced infilling that I hypothesized may be appropriate and that such infilling can dramatically alter the hydraulic geometry of a rill, which would substantially affect the velocity of flows within it.

The patterns of frost penetration and thaw and soil water redistribution suggest that the soil in the bin froze and thawed in a natural manner, which mimics that in the field. The heave of the soil during freeze and its settlement and slumping during thaw appeared to reasonably simulate the response of an undisturbed field soil to FT cycles. Thus, this type of soil bin with side and bottom reinforcement to withstand vehicle loading can be used in future experiments on vehicular ruts.

* Personal communication with K. Knuth, CRREL, 1995.

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13. ABSTRACT (*Maximum 200 words*)

Military maneuvers damage vegetation and compact and rut soils on training lands, thereby increasing the likelihood of hillslope runoff and soil erosion. Soil Freeze–Thaw (FT) processes can change the hydraulic geometry and roughness of vehicular ruts and reduce soil compaction, which often partially restores the water infiltration rate that existed before compaction. The efficiency of these FT-induced "repairs" depends on soil water content and FT intensity. Initial tests showed that 1) an experimental soil bin designed and constructed for rut experiments allows acceptable simulation of field soil FT, and 2) the hydraulic geometry of a rectangular rill in a fine silt soil with an initial volumetric water content of 36% changes dramatically due to rill sideslope slumping during thaw. Future experiments will compare differences in the response of natural rills and vehicular ruts to FT-induced soil failure, and investigate the effects of FT on soil erodibility and the influences of snow cover on soil erosion processes in the spring.

14. SUBJECT TERMS
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